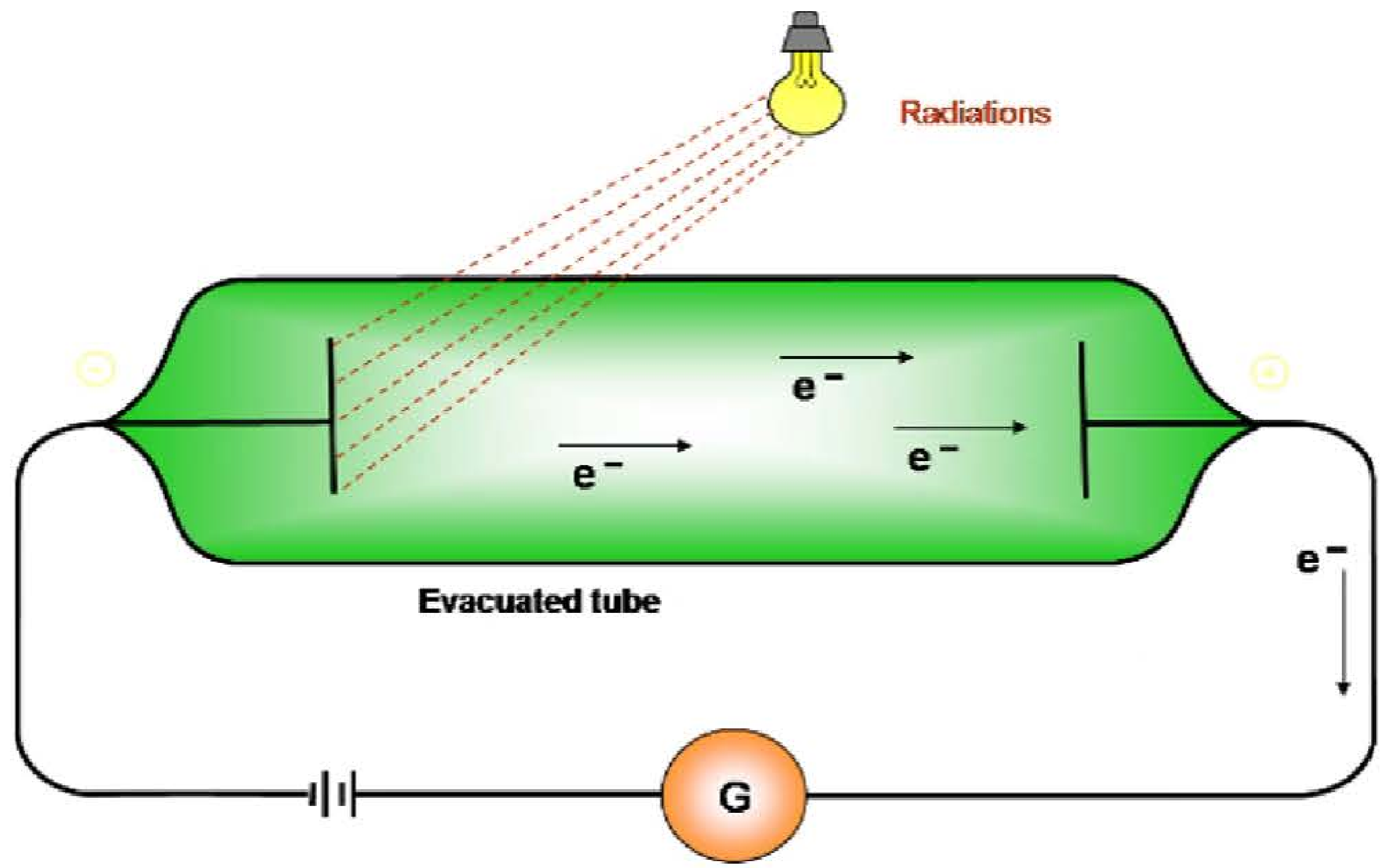
Modeling of energy conversion

Electromagnetic radiation to electric current

Electromagnetic radiation + matter -> electric current



Fundamental explanation: photoelectric effect

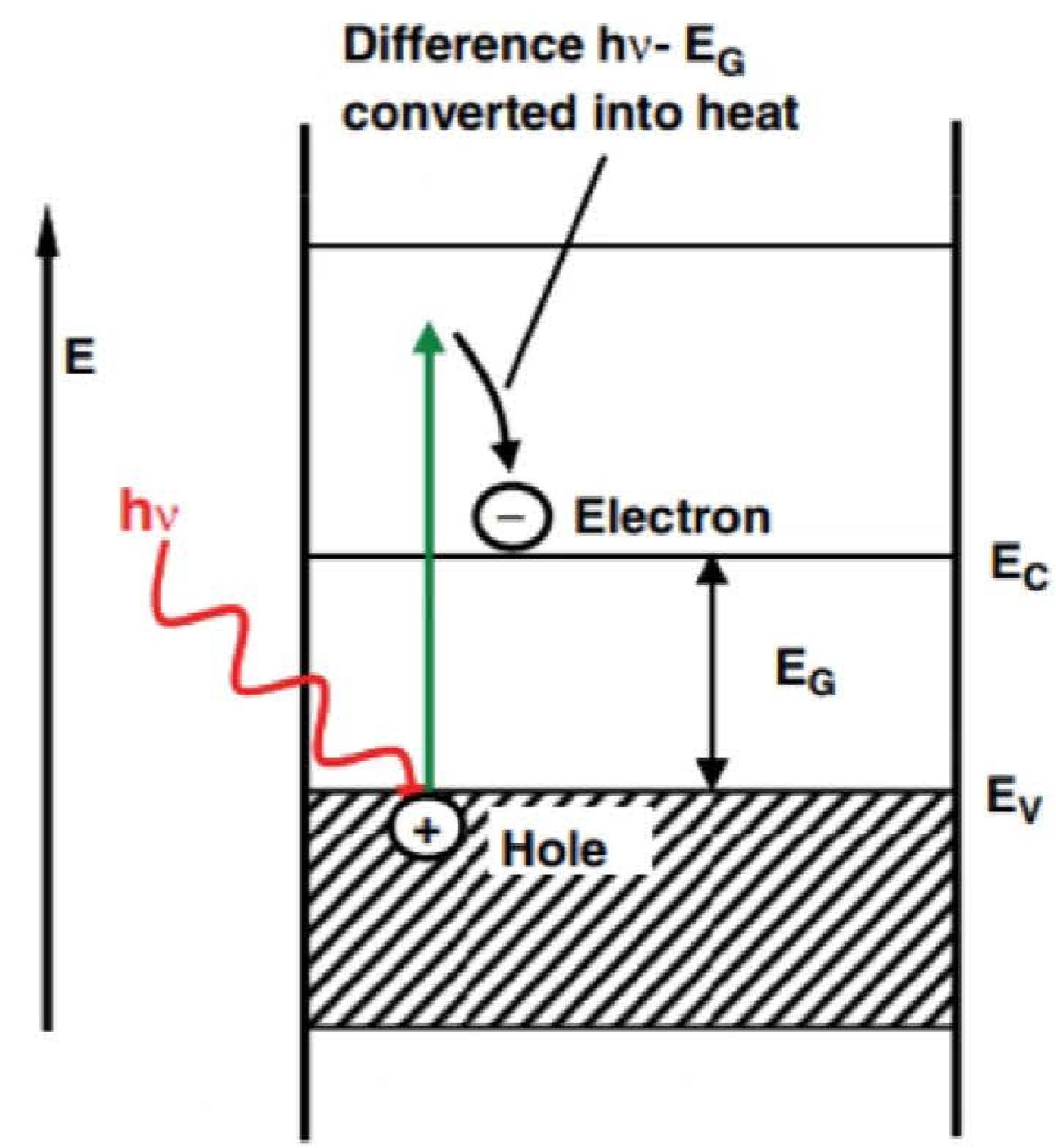
In the photoelectric effect, electrons are emitted from metals as a consequence of their absorption of energy from electromagnetic radiation of very short wavelength and high frequency, such as optical/ultraviolet radiation.

The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect".

Internal photoelectric effect:

photons where hn > E_G lift an electron out of the valence band into the conduction band and are absorbed

Photons where hn < E_G do not allow an electron to be lifted out of the valence band into the conduction band and are thus not absorbed.



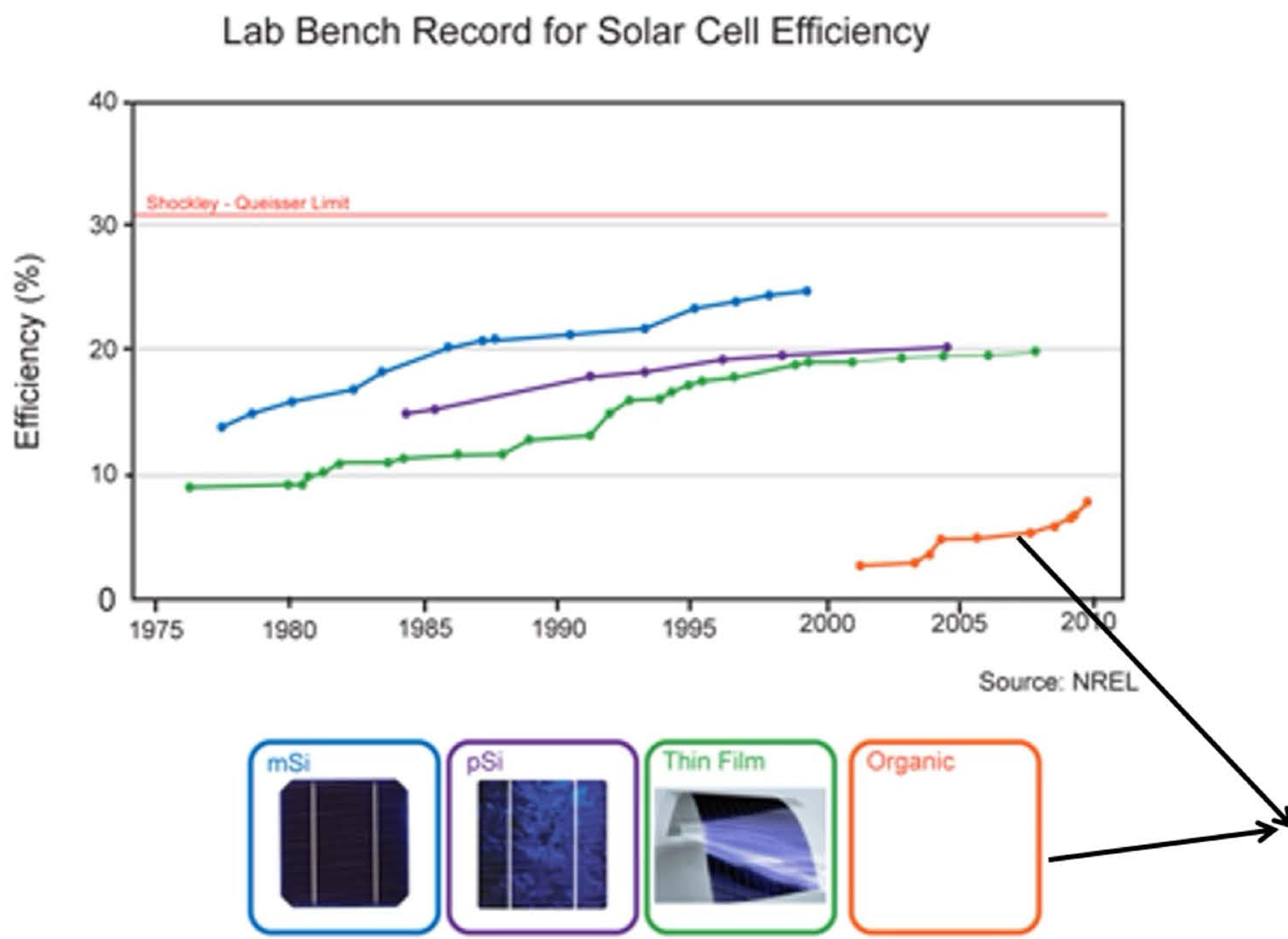
Application: Photovoltaic cells

Context: Fossil fuels are nonregenerable; solar radiation is

Electric generators based on photovoltaic cells have ***advantages***

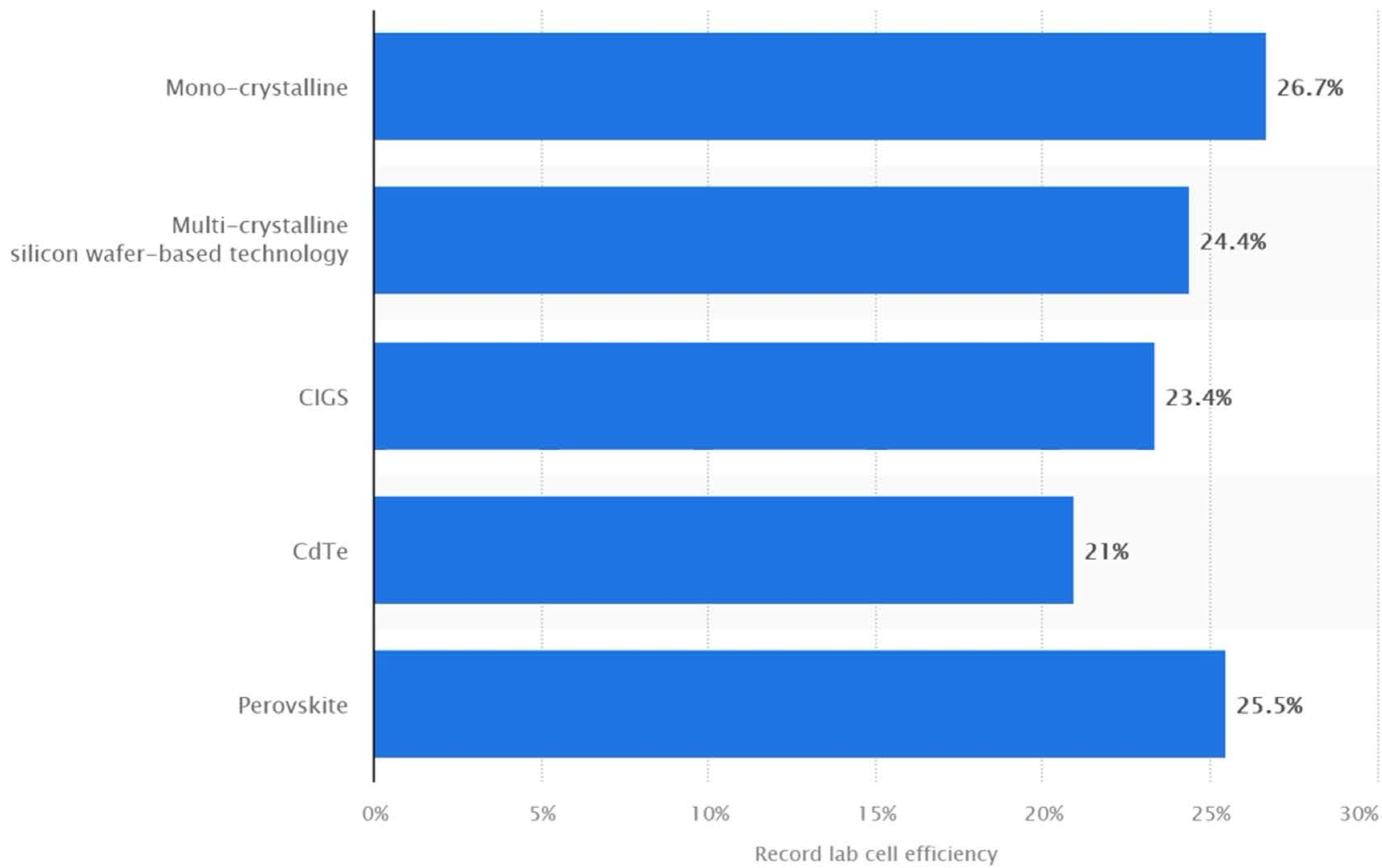
- Reliability and safety
- Low operating and maintenance costs
- Negligible environmental impact during the operating phase
- They work in isolated places (no access to main electric network needed)
- Modularity and convenient integration into building structures
- Versatility
- Easy to install and begin the operating phase

Photovoltaic cells - history

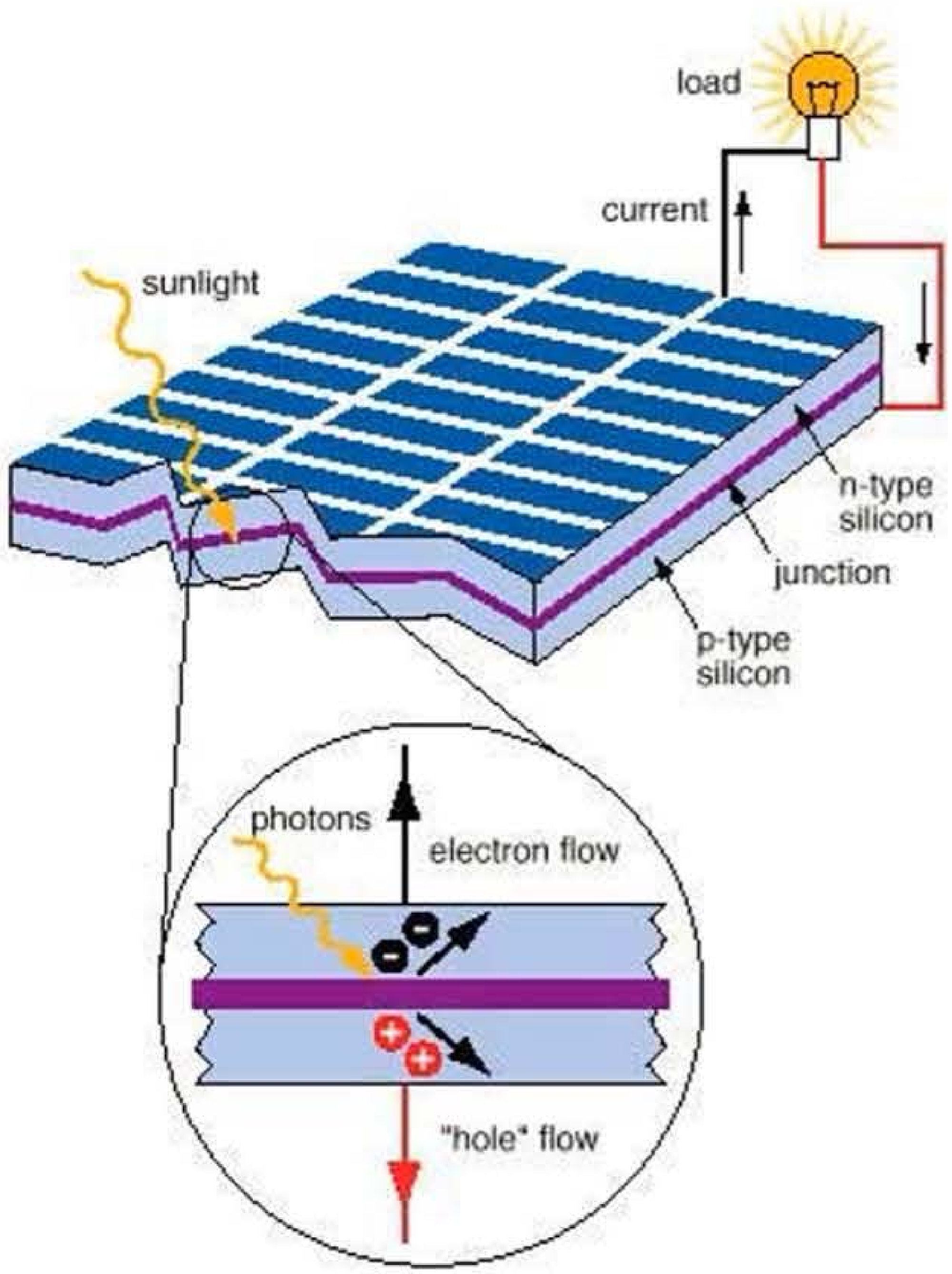


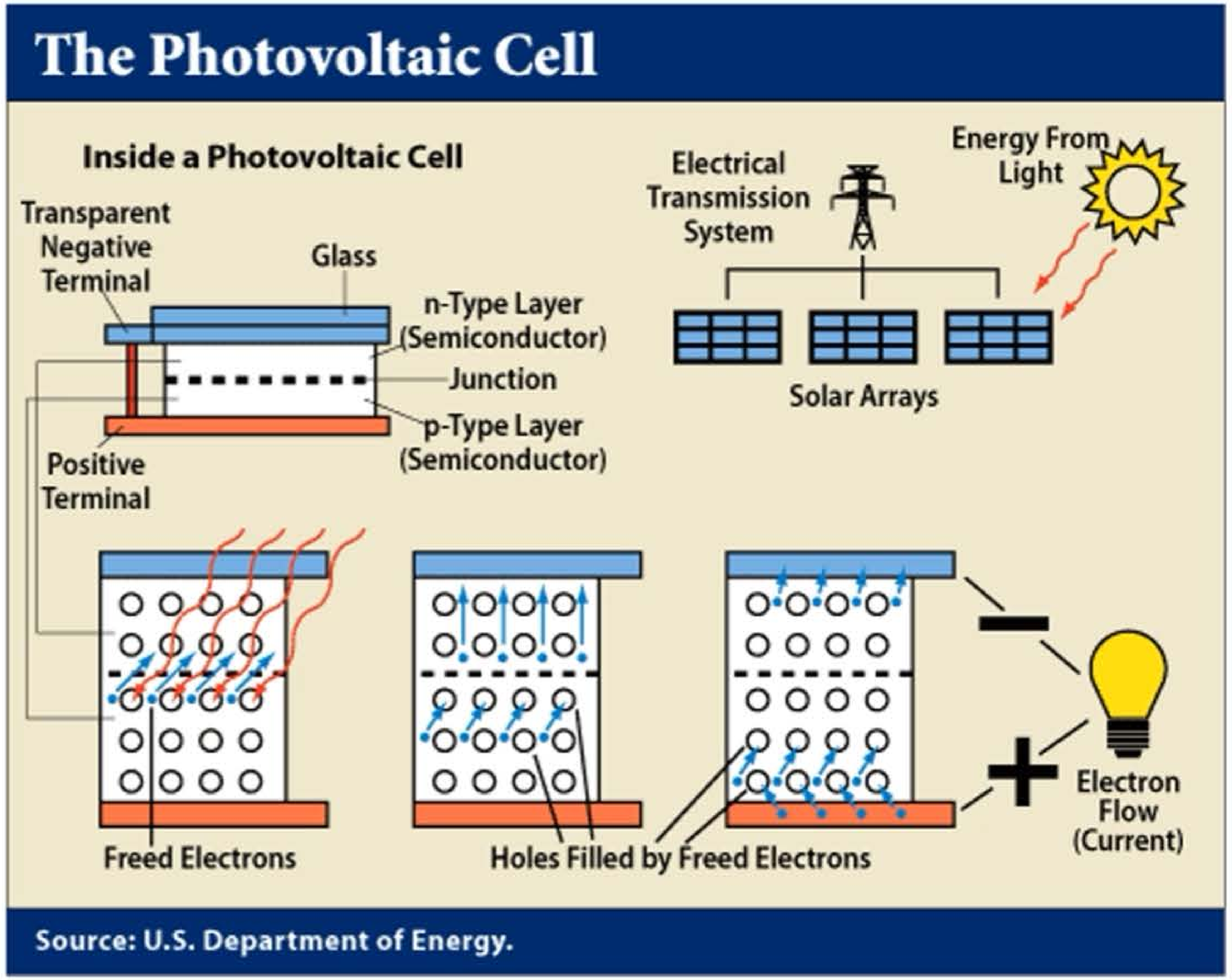
Emergent field

Record lab solar cell efficiency worldwide in 2020, by type



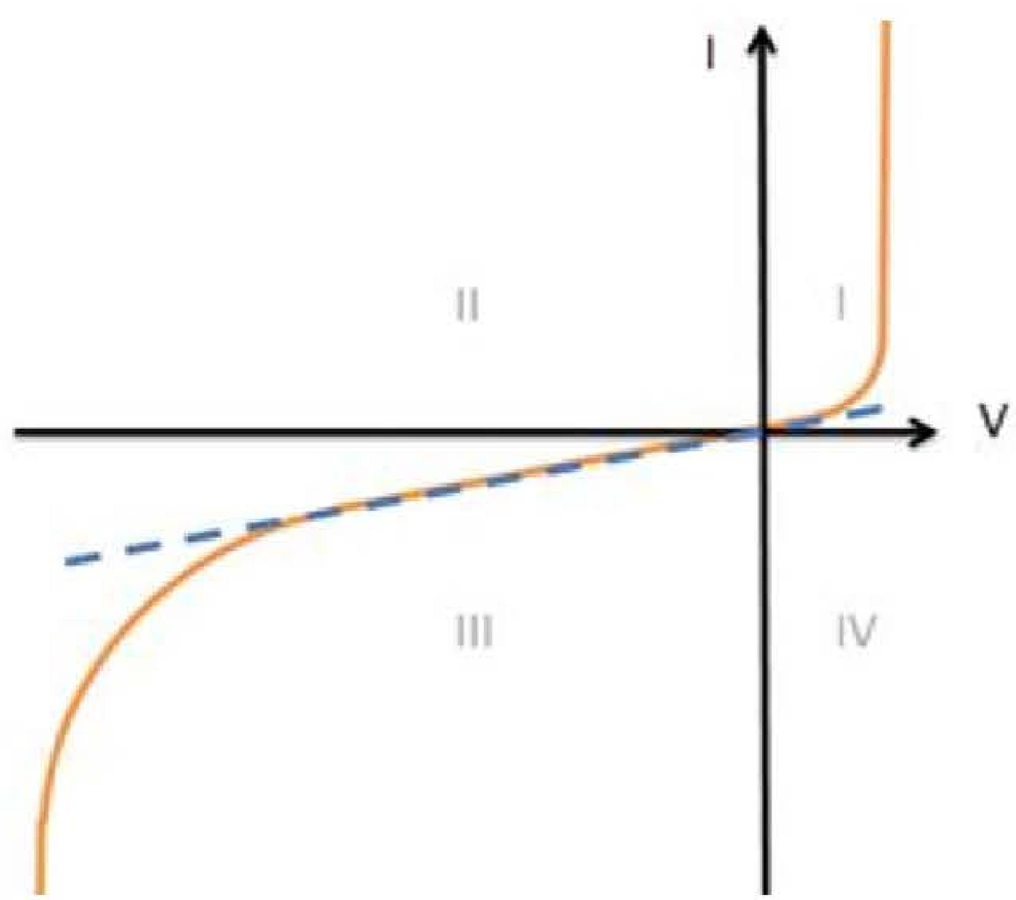
Photovoltaic cells – the physics

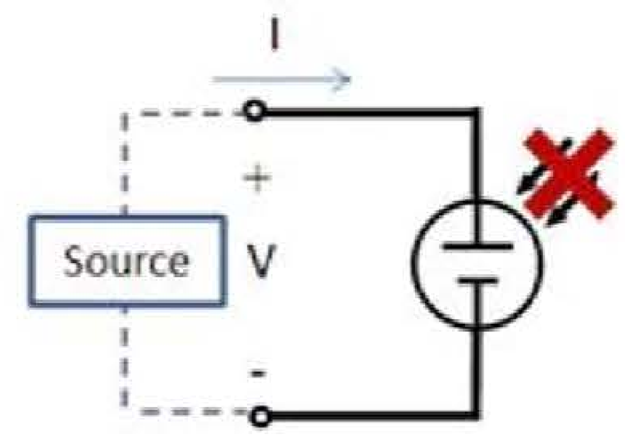


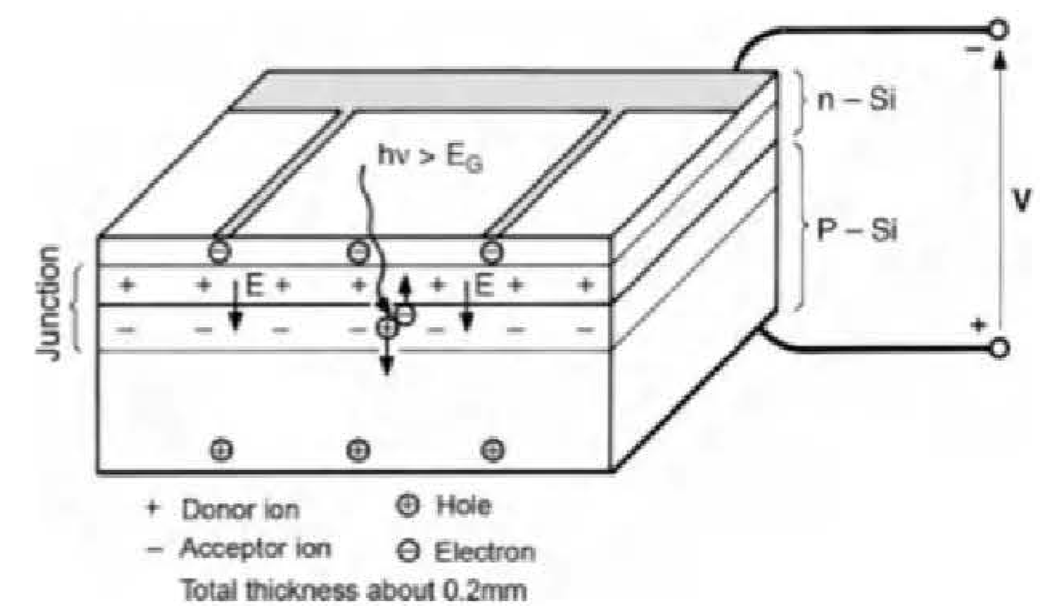


Photovoltaic cells

With no electromagnetic radiation -> the model for the pn junction







The cell

$$I_D = -I_S\left[1 - \exp\left(\frac{eV}{nk_BT}\right)\right]$$

I_S (I_0) Saturation current (idealized inverse current)

V applied voltage

e elementary charge= 1.602×10^{-19} As

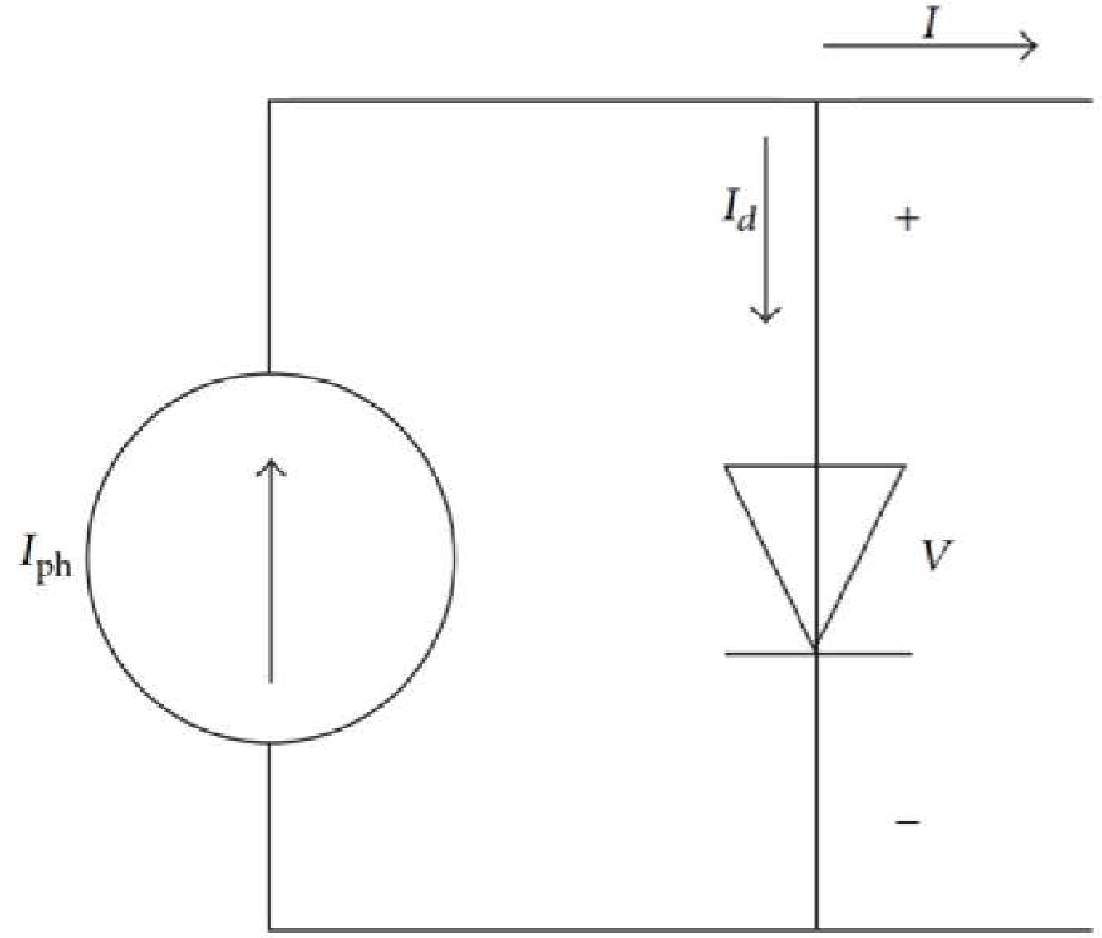
n the diode ideality (or quality) factor (typically between 1 and 2)

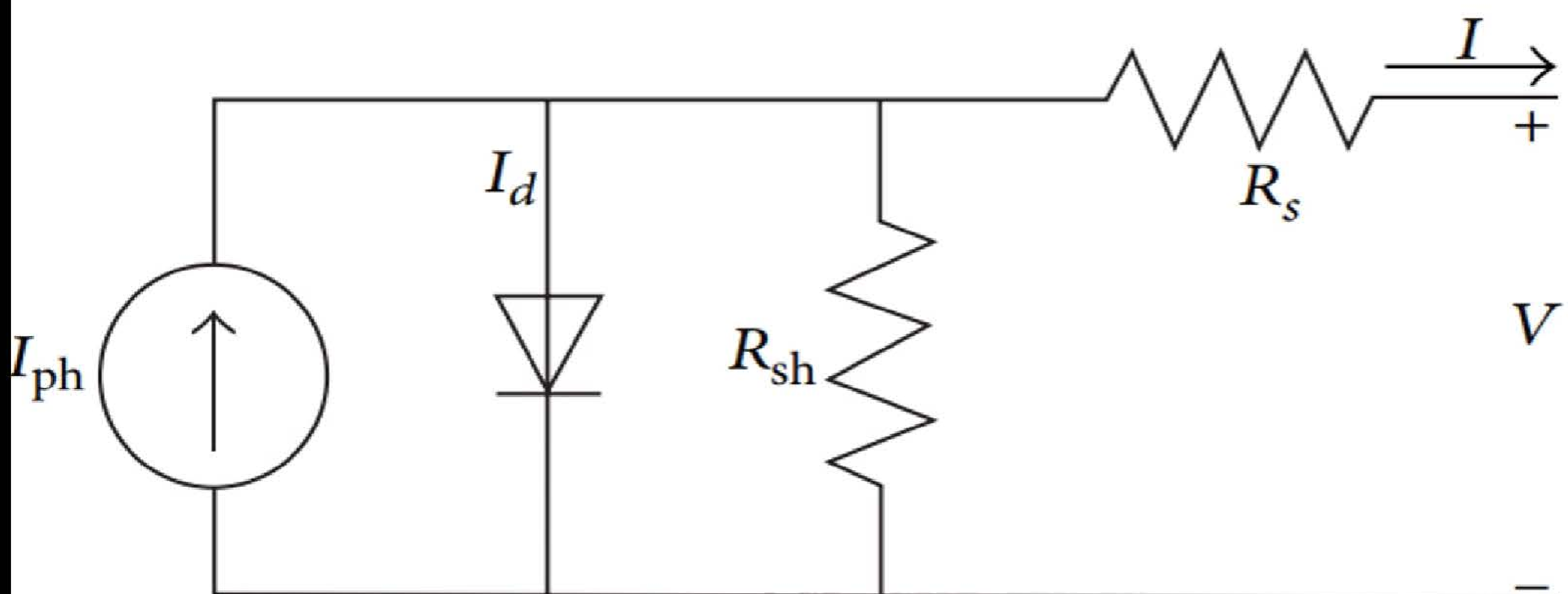
T temperature of cell

q absolute value of electron charge

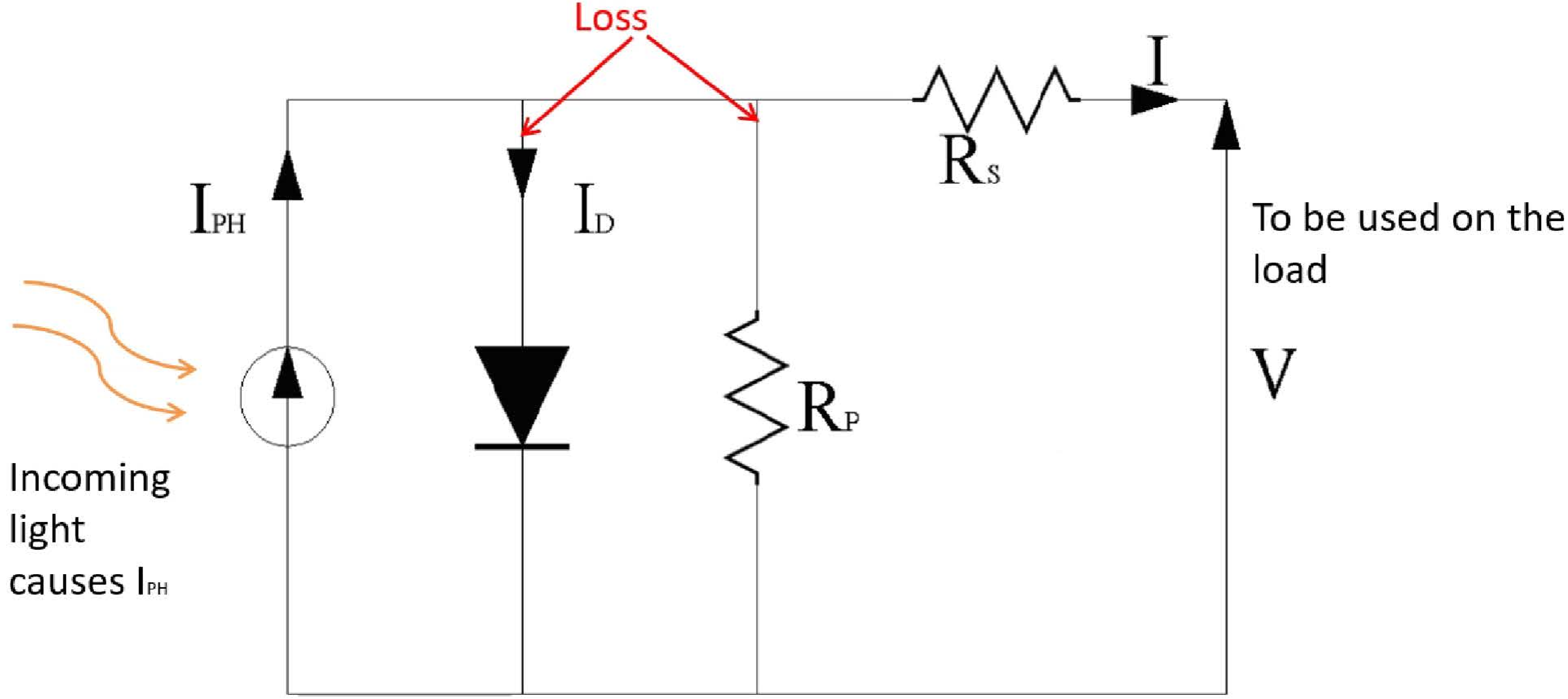
k_B Boltzmann constant

Photovoltaic cells – the models





A model with five parameters: photocurrent (I_{ph}), diode saturation current (I_0), ideality factor (n), parasitic series, and shunt resistances (R_s) and (R_{sh} or R_p)



Thermal diode voltage:

$$V_T = \frac{nk_BT}{e}$$

At 25°C, V_T=25.7 mV for n=1

$$I = I_{PH} + I_0\left[1 - \exp\left(q\frac{V + IR_s}{nk_BT}\right)\right] - \frac{V + R_sI}{R_p}$$

$$= I_{PH} - I_D - \frac{V + R_sI}{R_p}$$

Photovoltaic cells – characteristics

The ***short circuit current I_{SC}*** corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0.
I (at $V=0$) = I_{SC}

For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.
$I_{SC} = I_{MAX} = I_{PH}$

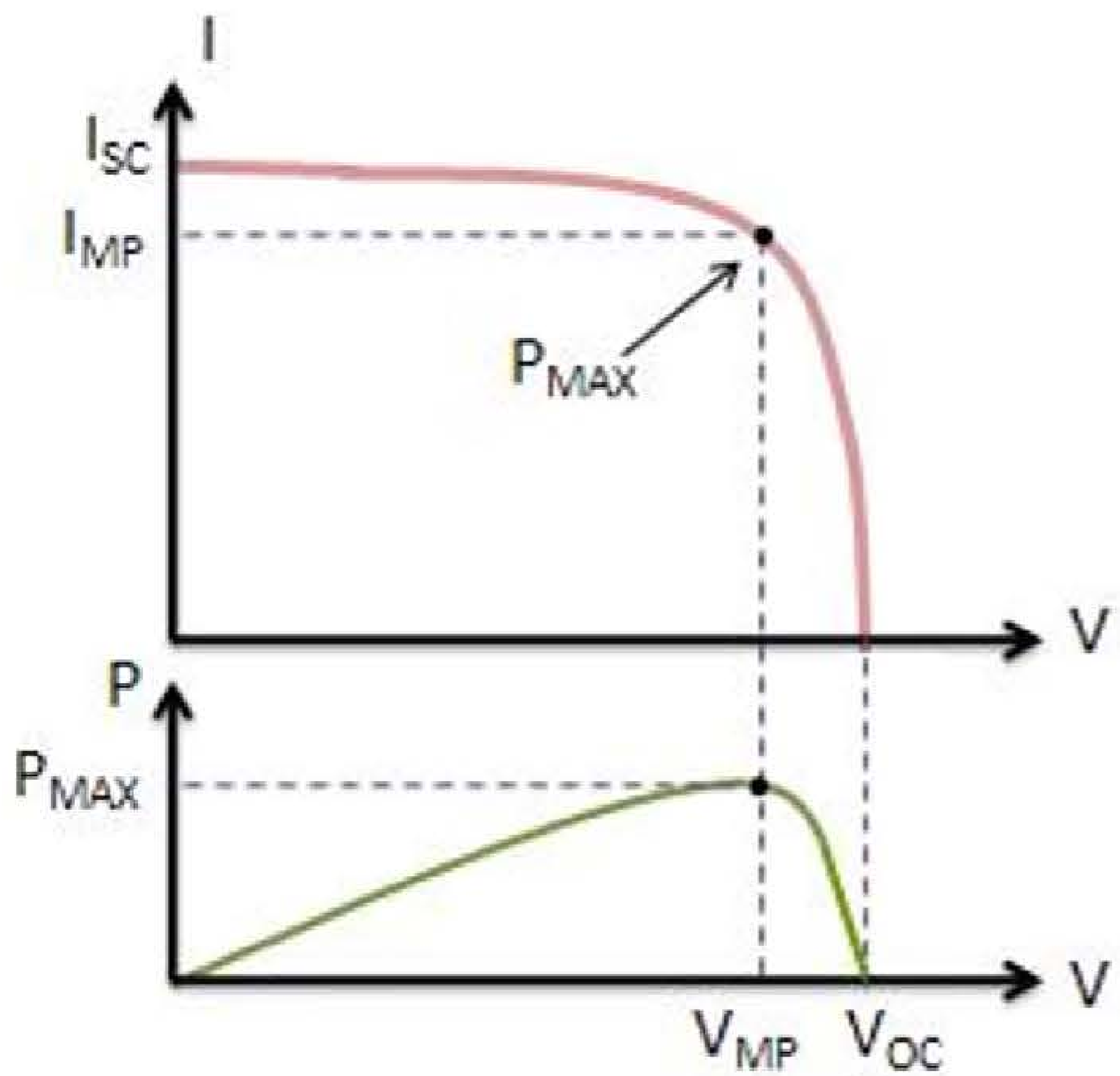
The ***open circuit voltage (V_{OC})*** occurs when there is no current passing through the cell.
V (at $I=0$) = V_{OC}

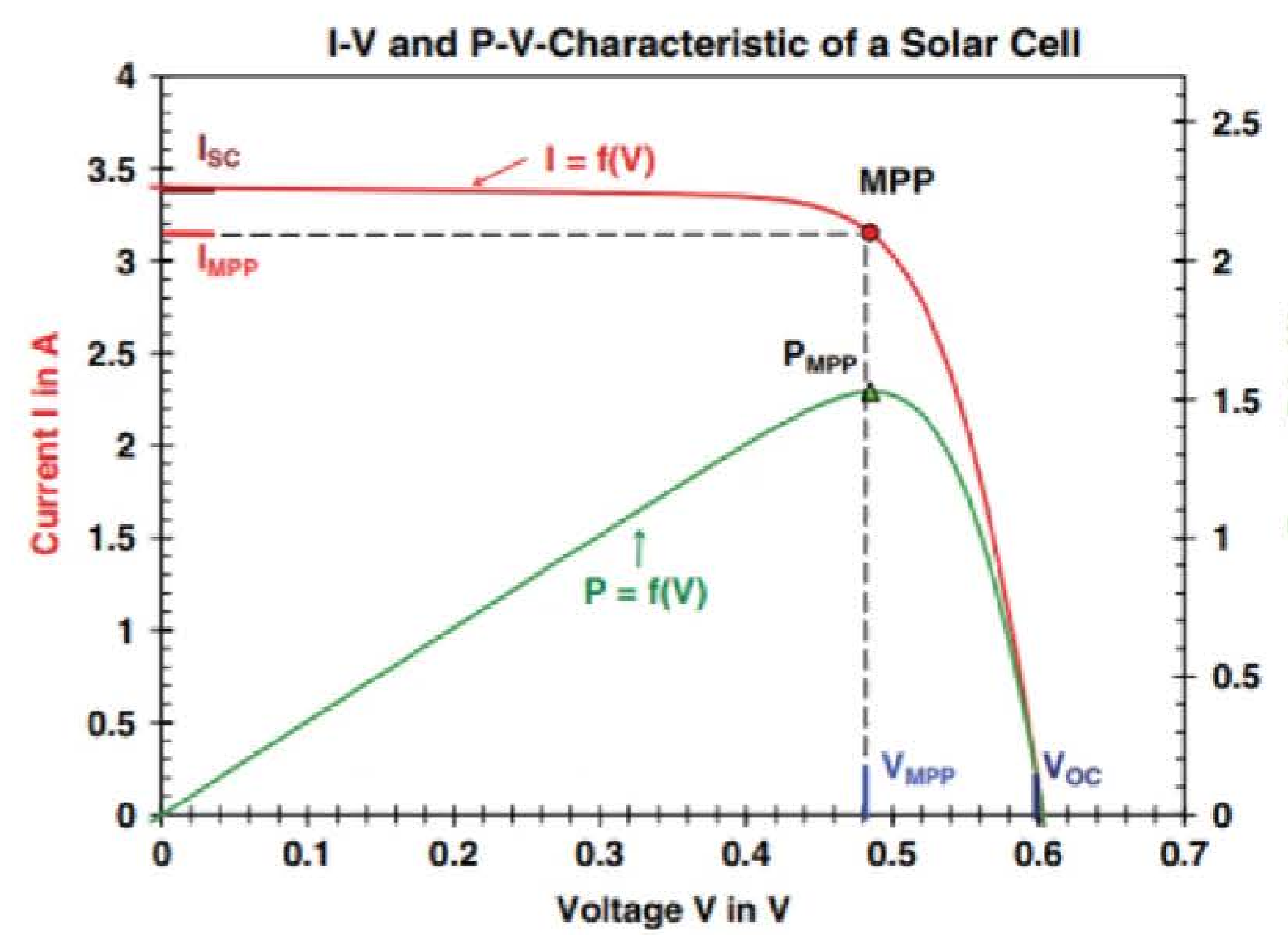
Photovoltaic cells – characteristics

The ***power*** produced by the cell in Watts can be easily calculated
P=IV.

At the I_{SC} and V_{OC} points, the power will be zero and the maximum value for power will occur between the two. The voltage and current at this ***maximum power point*** are denoted as $\boldsymbol{V_{MP}}$ and $\boldsymbol{I_{MP}}$ respectively.

The characteristic curves **I=f(V)** and **P=f(V)**

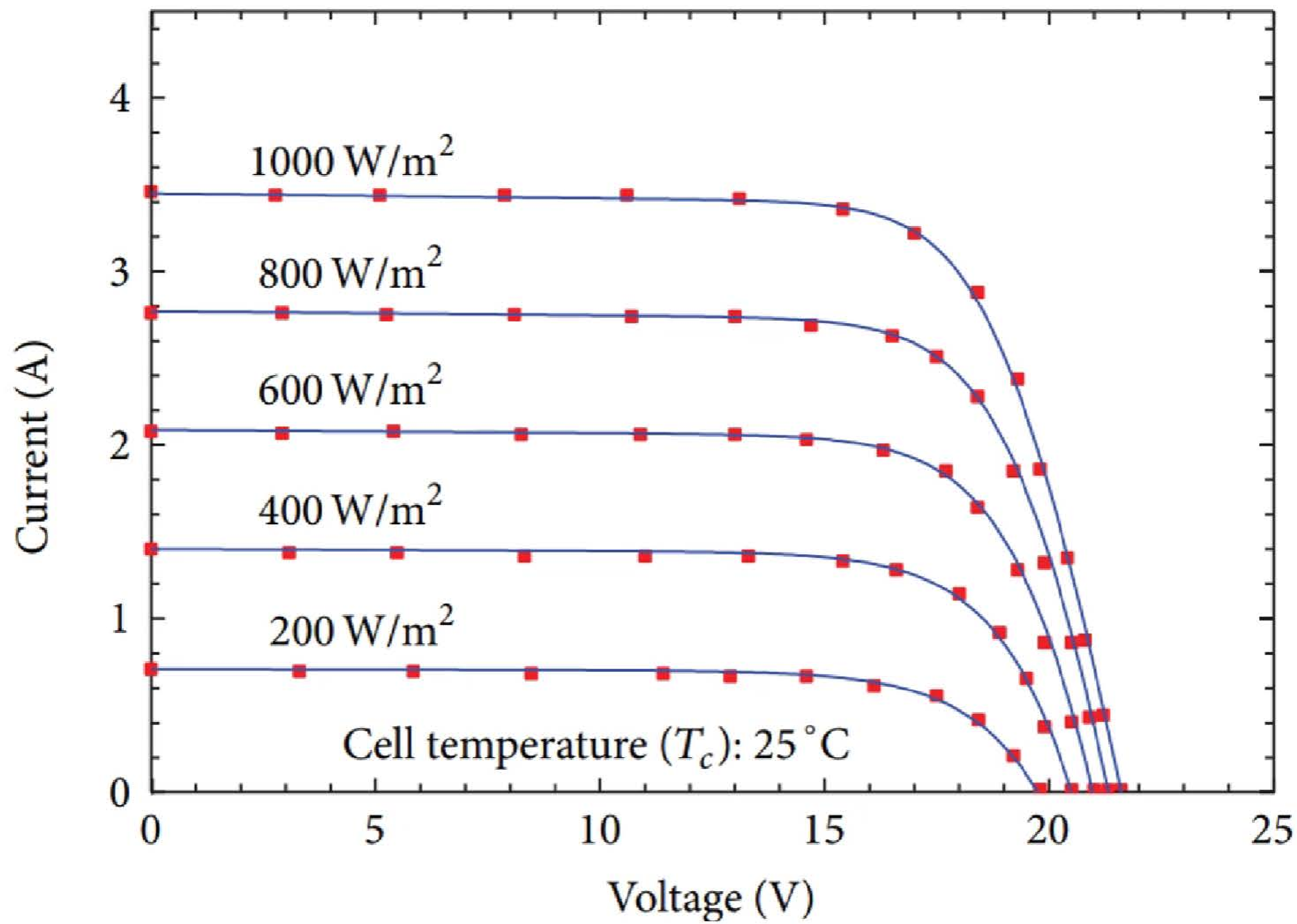




Ex. monocrystalline silicon solar cell with a cell area of approximately 102 cm^2,
irradiance G of 1 kW/m^2 and
cell temperature of 25 C

Photovoltaic cells – characteristics

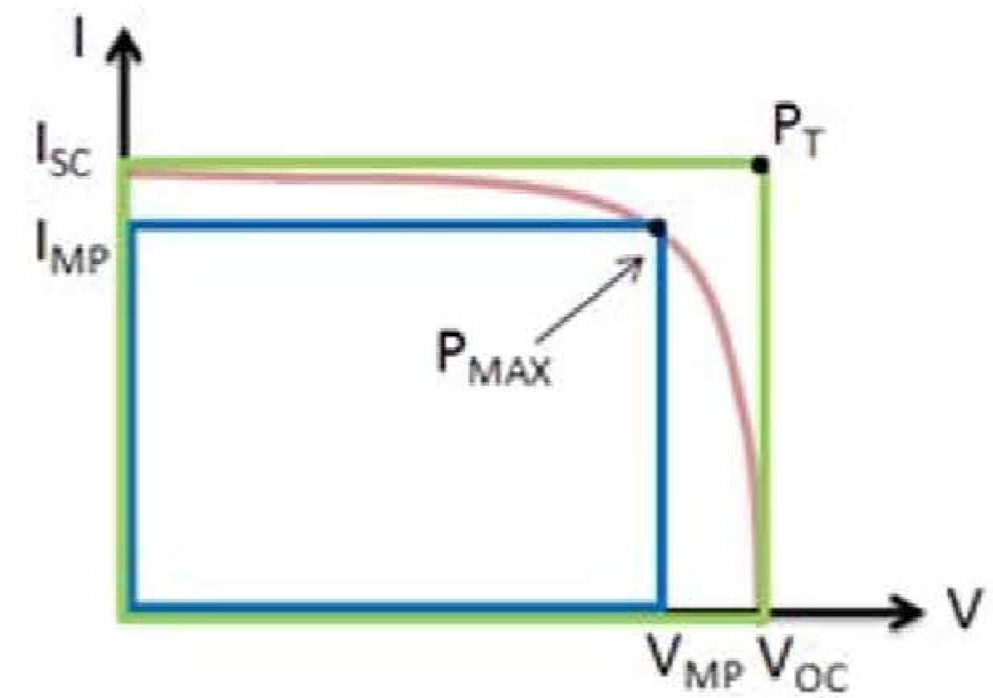
The characteristic curves **I=f(V)** for different levels of irradiance



Photovoltaic cells – characteristics

The ***Fill Factor (FF)*** is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_T) that would be output at both the open circuit voltage and short circuit current together. Typical fill factors range from 0.5 to 0.82.

$$FF = \frac{P_{MAX}}{P_T} = \frac{\boxed{I_{MP} \cdot V_{MP}}}{\boxed{I_{SC} \cdot V_{OC}}}$$



Efficiency is the ratio of the electrical power output $P_{out} = P_{MAX}$, compared to the solar power input, P_{in}, into the PV cell.

$$\eta = \frac{P_{MAX}}{P_{in}}$$

Influenced by

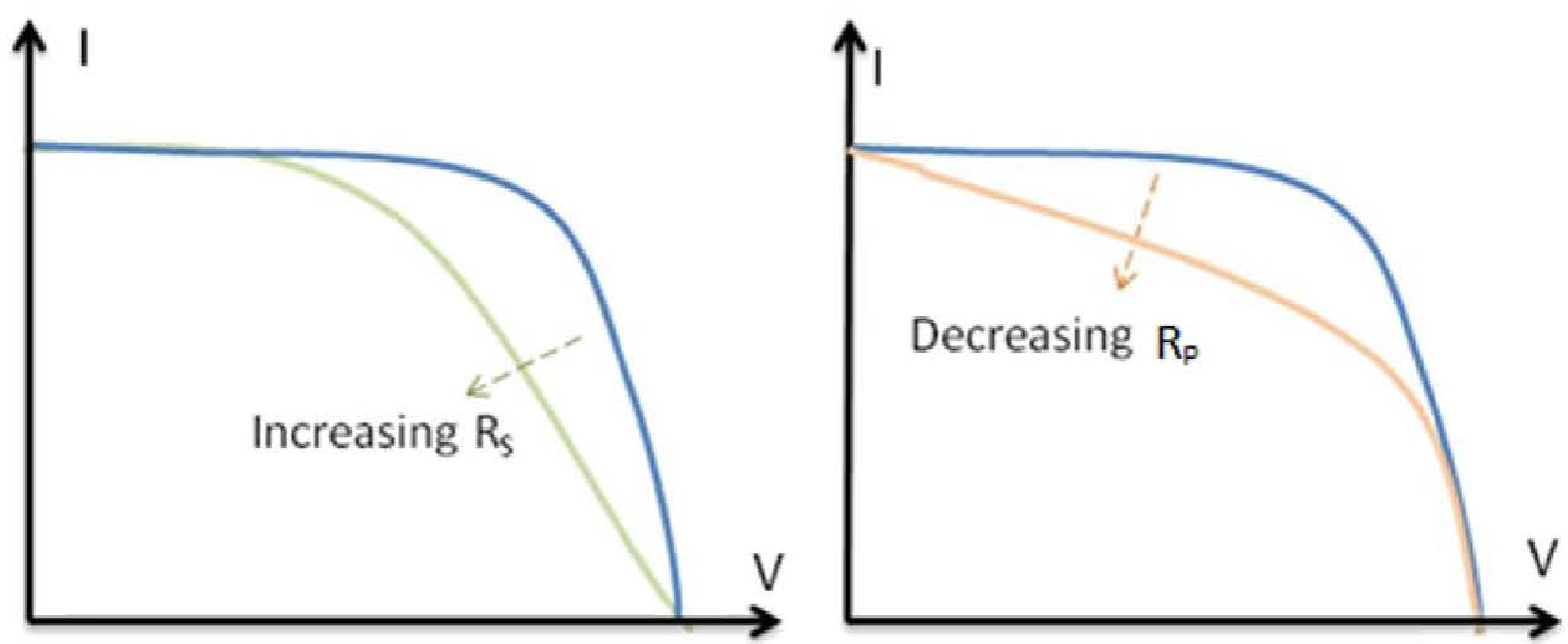
- Intensity of the incident radiation
- Temperature of the cell
- Surface area of cell

Photovoltaic cells – characteristics

During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_P) and series resistance (R_S).

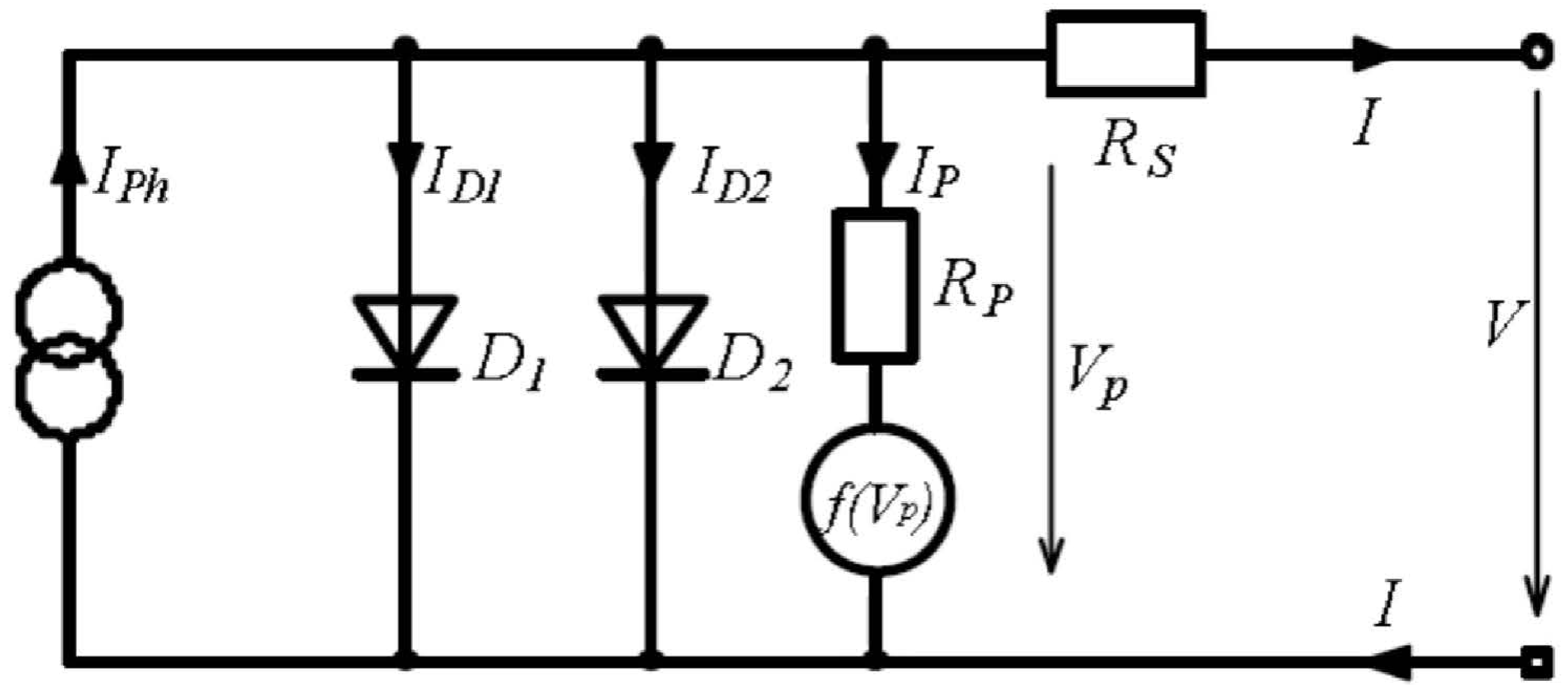
For an ideal cell, R_p would be infinite and would not provide an alternate path for current to flow, while R_S would be zero, resulting in no further voltage drop before the load.

Decreasing R_p and increasing R_s will decrease the fill factor (FF) and P_{MAX} . If R_p is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead.



Improved models

model the diode breakdown due to non-uniform illumination



$$0 = f(V, I) = I_{Ph} - I_{D1} - I_{D2} - I_P - I = I_{Ph} - I_{S1} \cdot \left(\exp\left(\frac{V + I \cdot R_S}{m_1 \cdot V_T} \right) - 1 \right) -$$

$$I_{S2} \cdot \left(\exp\left(\frac{V + I \cdot R_S}{m_2 \cdot V_T} \right) - 1 \right) - \frac{V + I \cdot R_S}{R_P} \underbrace{- a \cdot \frac{V + I \cdot R_S}{R_P} \cdot \left(1 - \frac{V + I \cdot R_S}{V_{Br}} \right)^{-n}}_{\text{Extension term for the negative dio de breakdown}} - I$$

Identification of the model parameters

A model with five parameters:

$$\left\{\begin{array}{l}\text{photocurrent } (I_{\mathrm{ph}}), \\ \text{diode saturation current } (I_0), \\ \text{ideality factor (n)}, \\ \text{parasitic series, and shunt resistances } (R_s) \\ \text{and } (R_{\mathrm{sh}} \text{ or } \mathrm{R_p})\end{array}\right.$$

Introducing the conductance $G_{sh}=1/R_{sh}=1/R_p$ and the notation $\beta=e/k_BT$ allows to rewrite the equation:

$$
\begin{aligned}
I &= I_{\mathrm{ph}} - I_{\mathrm{d}} - I_{\mathrm{p}} \\
&= I_{\mathrm{ph}} - I_{\mathrm{s}}\left[\exp\left(\frac{\beta}{n}(V + IR_{\mathrm{s}})\right) - 1\right] - G_{\mathrm{sh}}(V + IR_{\mathrm{s}})
\end{aligned}
$$

A second set of notations

$$
\begin{cases}
I_{\mathrm{pA}} = \frac{I_{\mathrm{ph}}}{1+G_{\mathrm{sh}}R_{\mathrm{s}}} \\
I_0 = \frac{I_{\mathrm{s}}}{1+G_{\mathrm{sh}}R_{\mathrm{s}}} \\
G_{\mathrm{A}} = \frac{G_{\mathrm{sh}}}{1+G_{\mathrm{sh}}R_{\mathrm{s}}}
\end{cases}
$$

Allows a new formulation:

$$
I = I_{\mathrm{pA}} - I_0\left[\exp\left(\frac{\beta}{n}(V + IR_{\mathrm{s}})\right) - 1\right] - G_{\mathrm{A}}V
$$

$$I = \boxed{I_{pA} - I_0\left[\exp\left(\frac{\beta}{n}(V + IR_s)\right) - 1\right]} - \boxed{G_A V}$$

Term that can be neglected for low bias voltages

Term that can be neglected under forward bias for (V+R$_s$I)>>kT

There a two sub-models, each appropriate for a given operation regime:

Submodel 1

$$I = \boxed{I_{PA}} - \boxed{G_A} V$$

2 parameters to be identified by a simple linear fit

Submodel 2

$$I_c = I_{pA} - \boxed{I_0}\left[\exp\left(\frac{\beta}{\boxed{n}}(V + I\boxed{R_s})\right)\right]$$

Can be rewritten as:

$$V = \frac{n}{\beta}\ln\frac{I_{pA}}{I_0} + \frac{n}{\beta}\ln\left(1 - \frac{I_c}{I_{pA}}\right) - R_s I$$

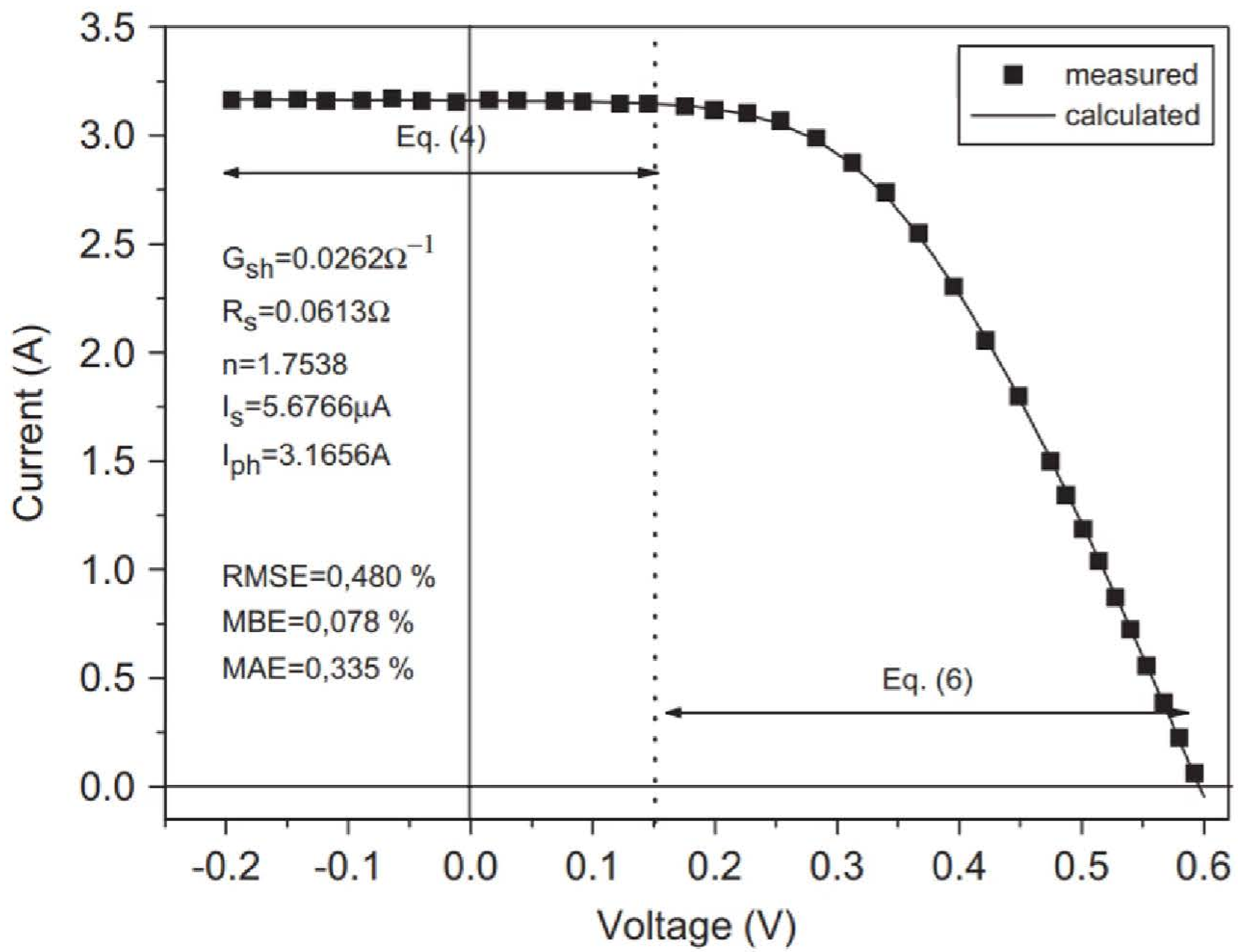
The function V=f(I) is then of the form:

$$f(I) = C_0 + C_1 I + C_2 \ln\left(1 - \frac{I_c}{I_{pA}}\right)$$

3 parameters to be identified by means of the experimental current–voltage data array using a least-squares method.

Evaluation of the identified model

- Experimental data and the fitted curve for a silicon solar cell (K. Bouzidi, 2006)



(I_i,V_i) are the measured current and voltage at the ith point

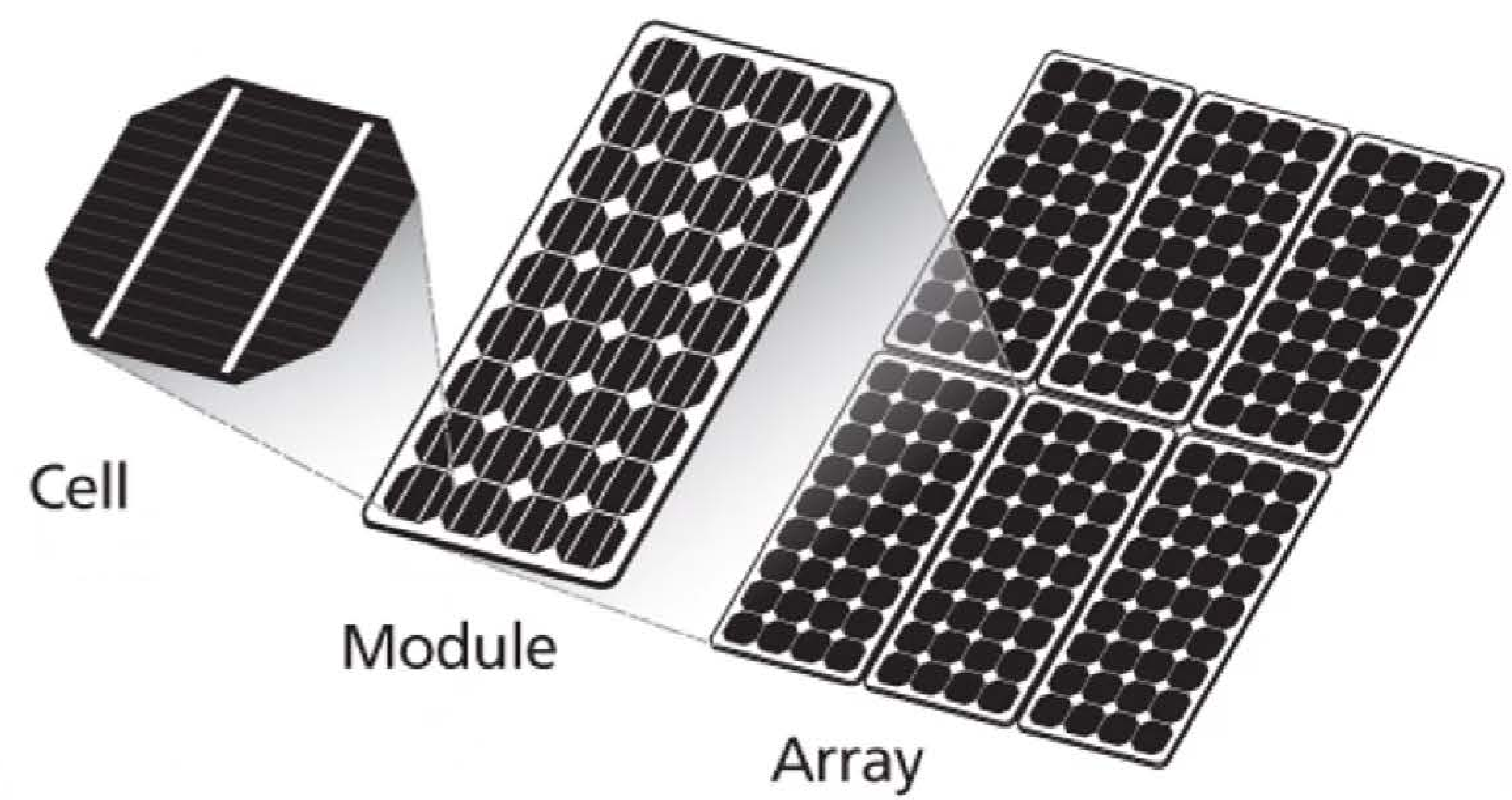
$I_{cal,i}$ is the current calculated for each V_i, by solving the cell equation with the determined set of parameters (G_{sh}, I_{ph}, n, R_s, I_s)

Root Mean Squared error (RMSE)
Mean Bias Error (MBE)
Mean Absolute Error (MAE)

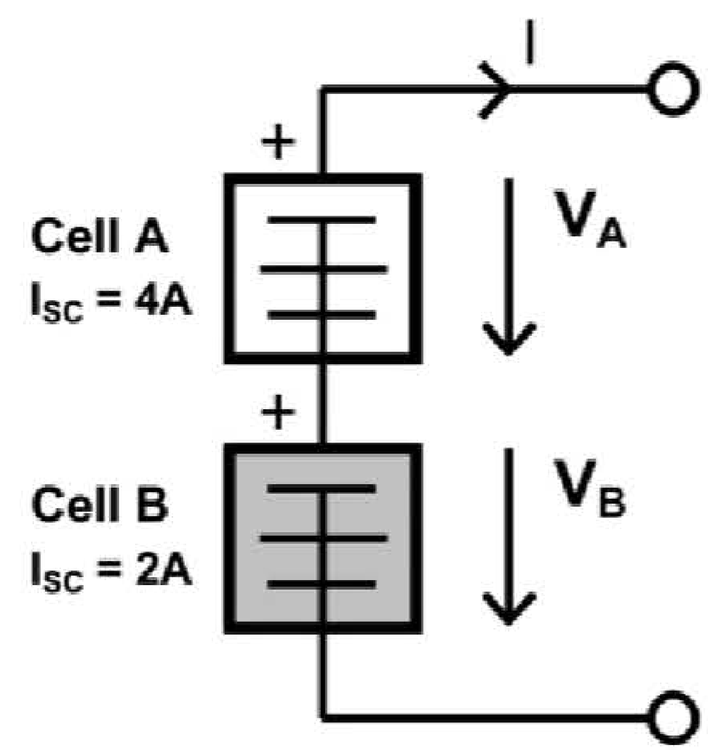
$$\begin{cases} \mathrm{RMSE} = \left[(1/m)\sum_{1}^{m}(I_i/I_{\mathrm{cal},i} - 1)^2\right]^{1/2} \\ \mathrm{MBE} = (1/m)\sum_{1}^{m}(I_i/I_{\mathrm{cal},i} - 1) \\ \mathrm{MAE} = (1/m)\sum_{1}^{m}\left|(I_i/I_{\mathrm{cal},i} - 1)\right| \end{cases}$$

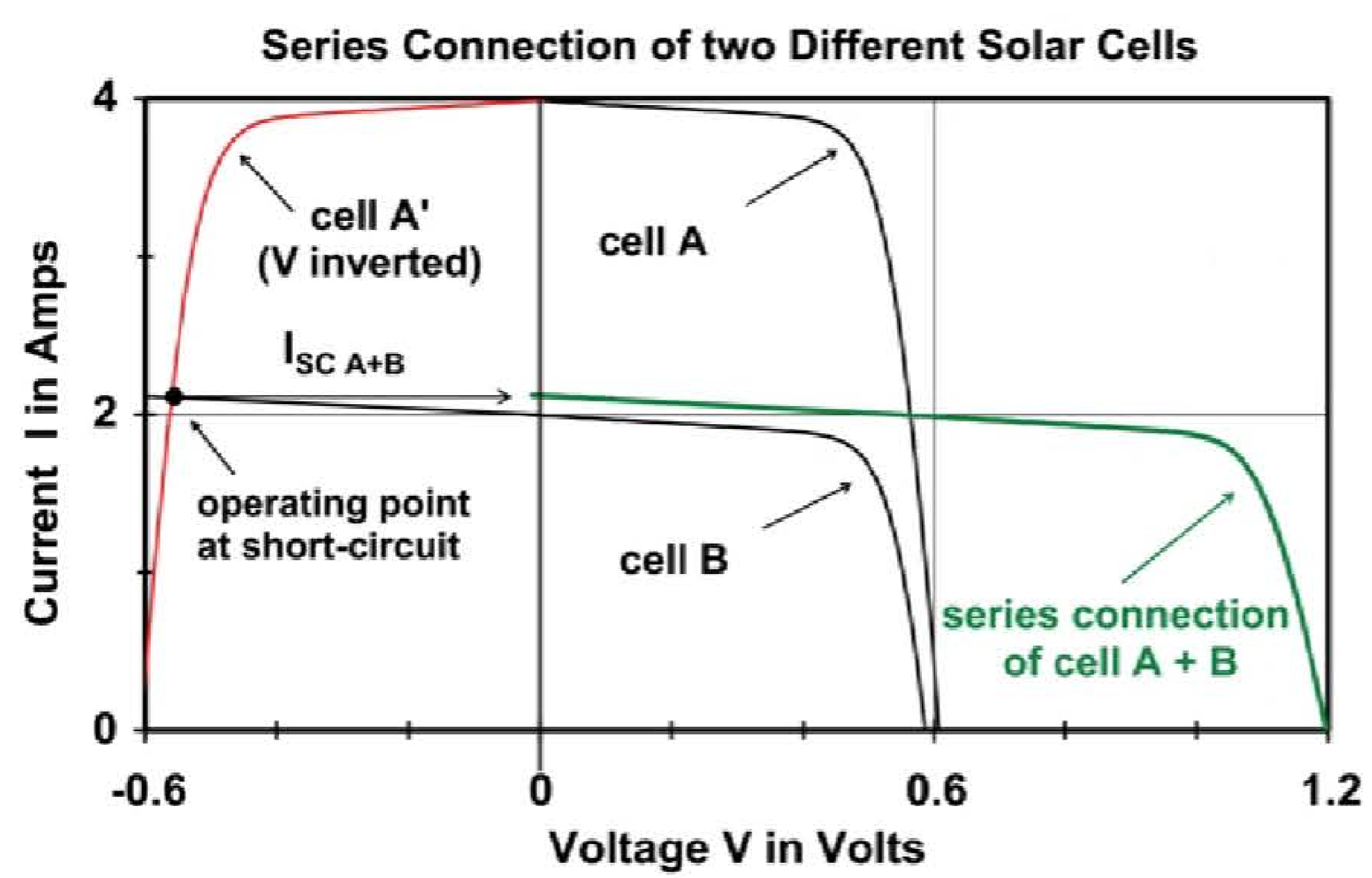
Remarks:

- The current–voltage equation for a solar cell represents an analytical model valid at a given irradiance level
- When all the connected cells are **identical** and work under **the same conditions of illumination and temperature**, the model can be *extended from cell to module*

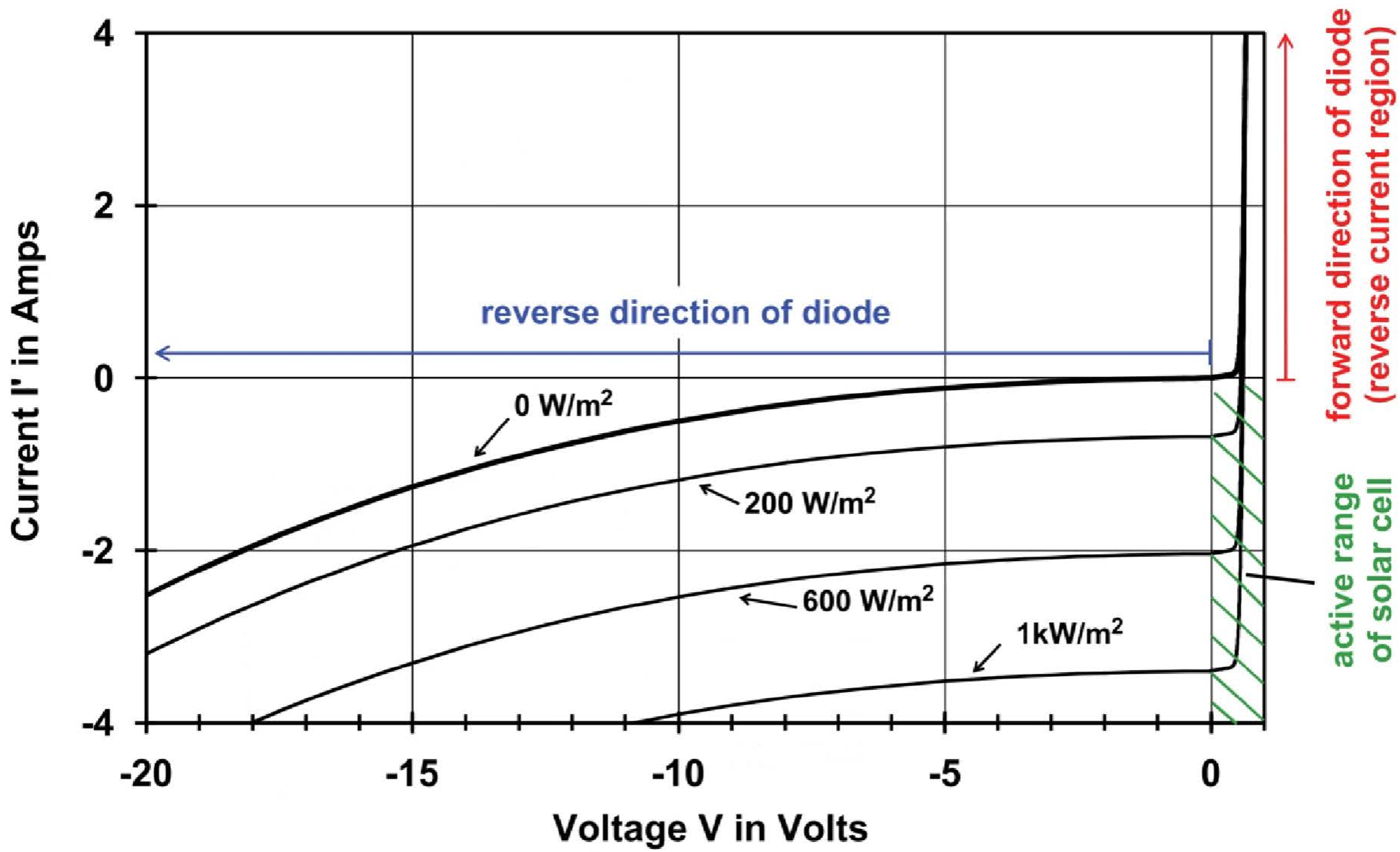


Connecting multiple cells

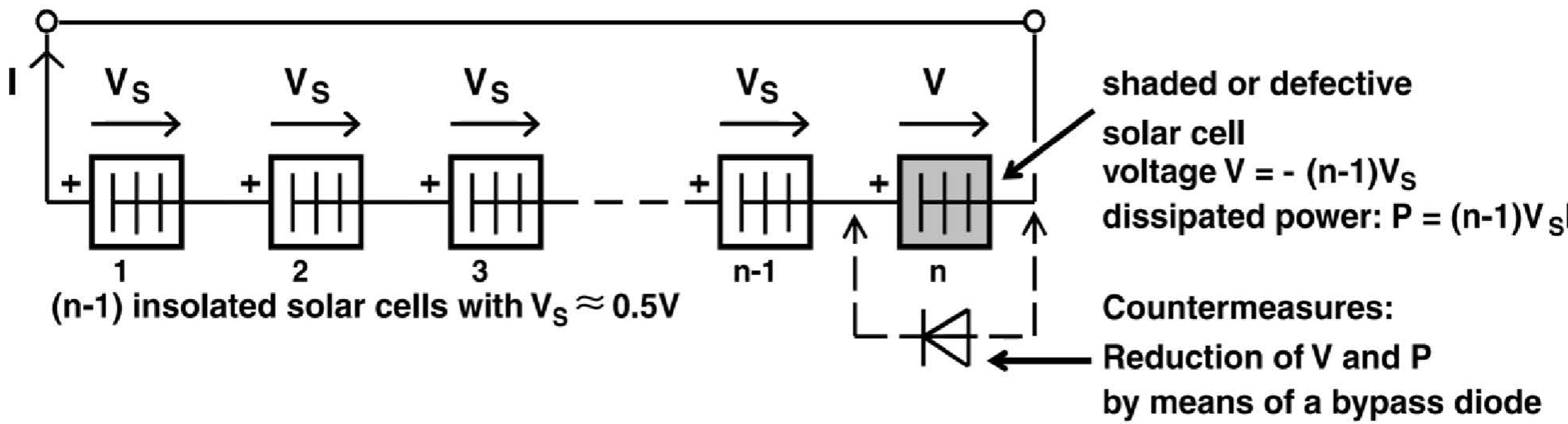


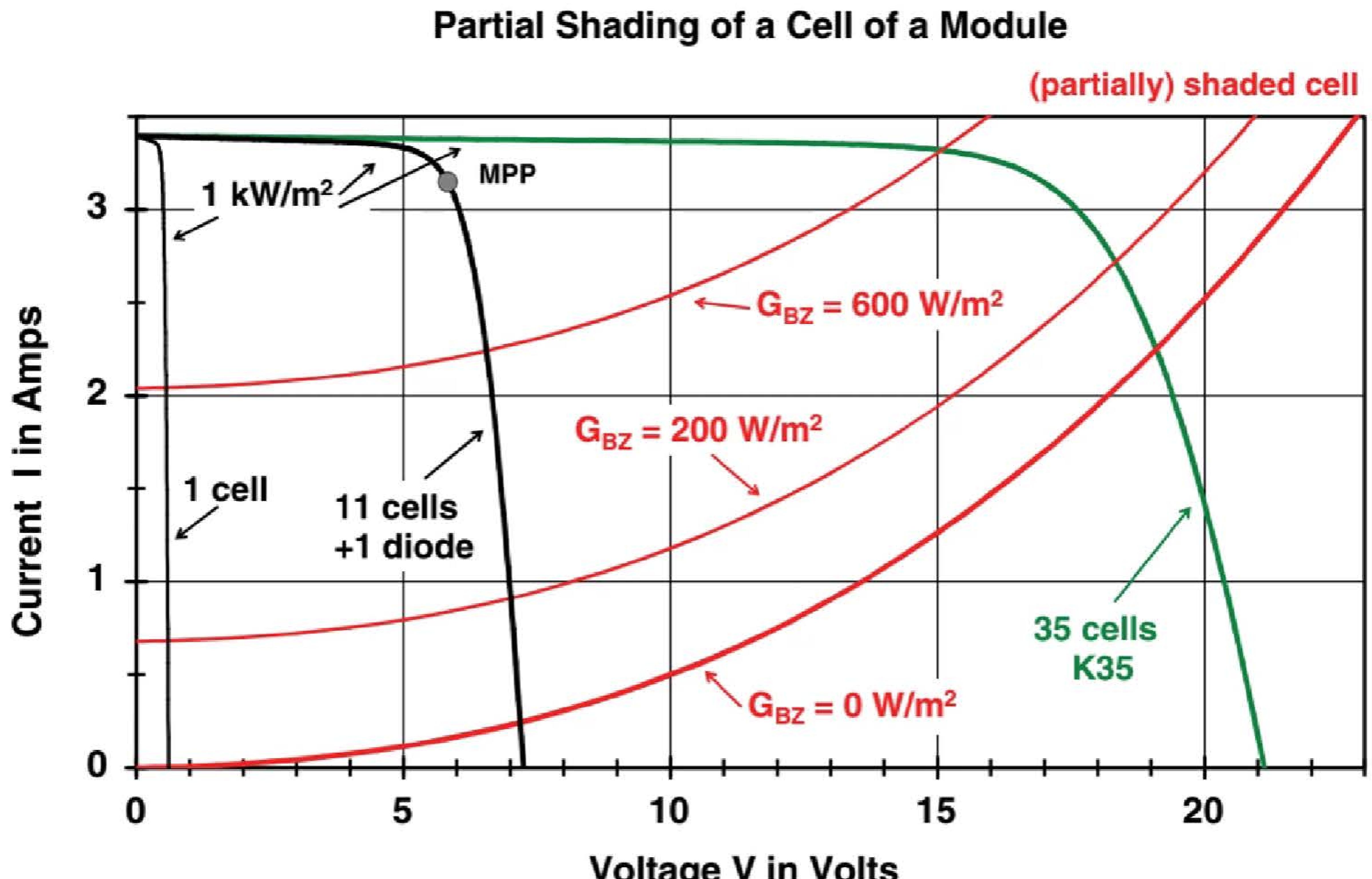


Characteristics of a Solar Cell (monocrystalline, illuminated and dark)

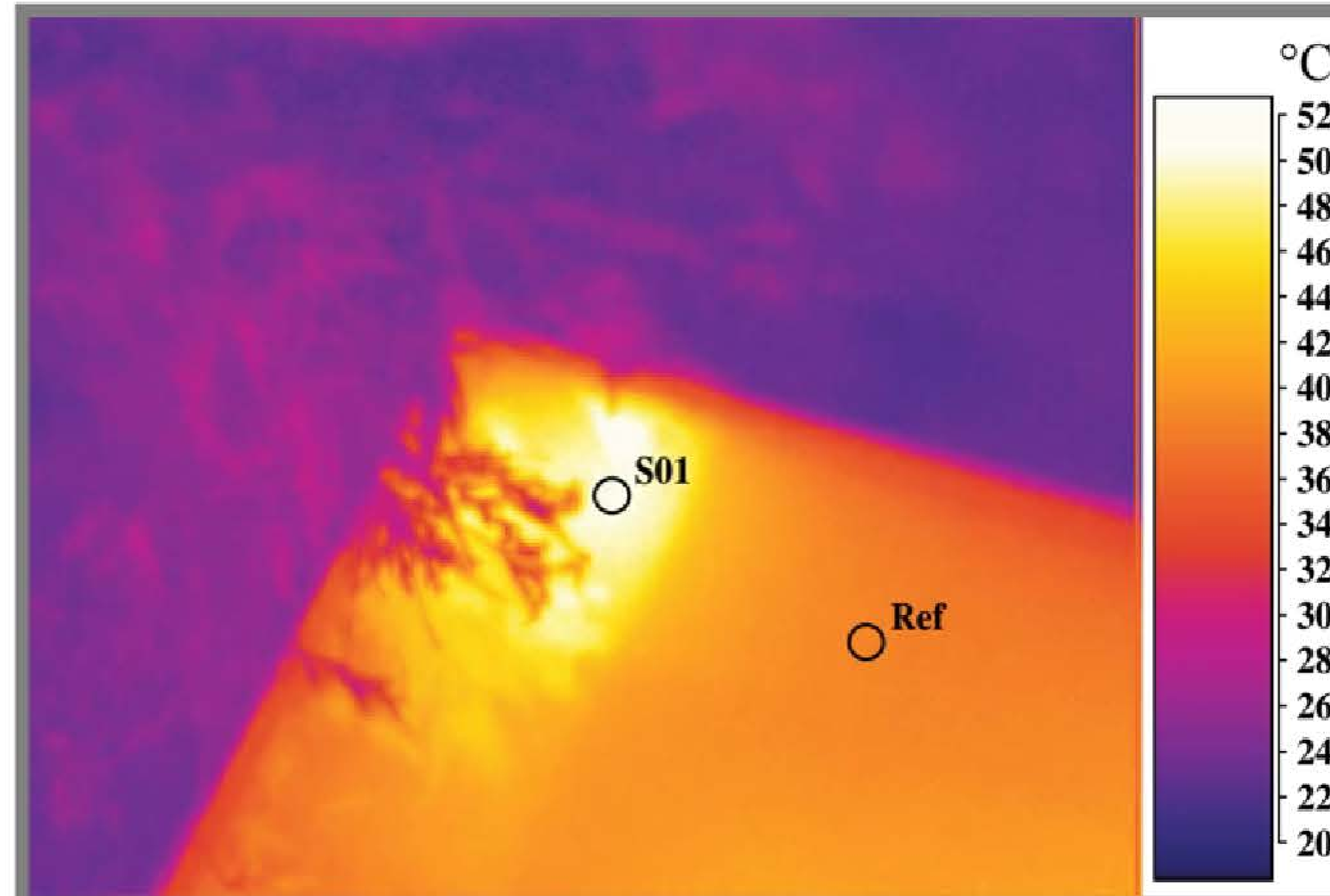


Connecting multiple cells





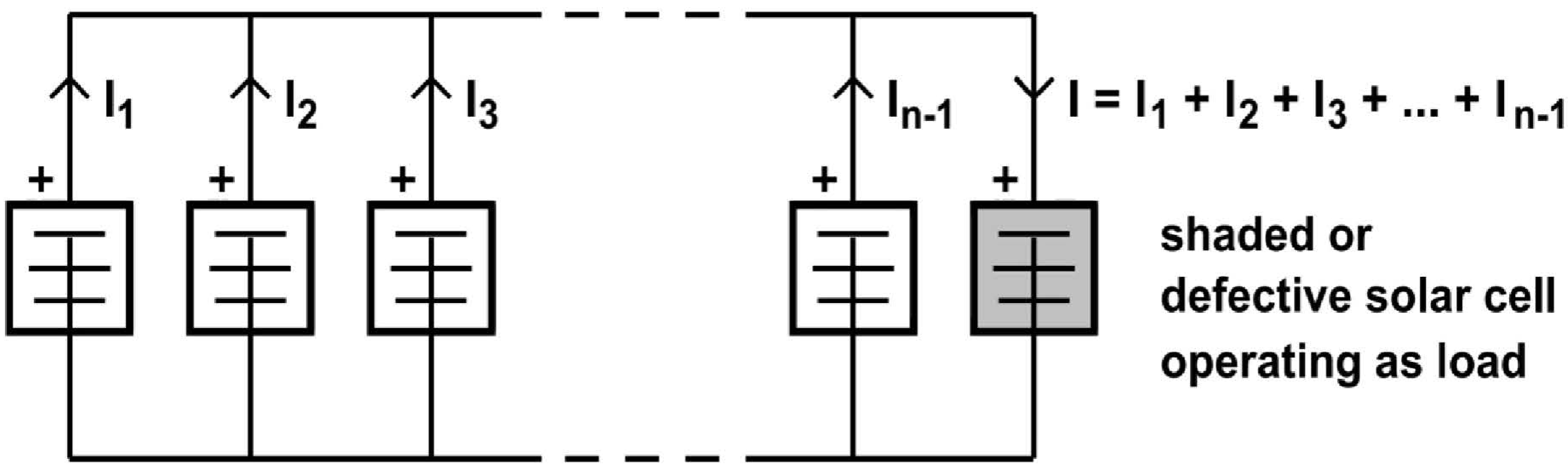
Partial Shading of a Cell of a Module
(partially) shaded cell
MPP
1 kW/m²
1 cell
11 cells
+1 diode
G_BZ = 600 W/m²
G_BZ = 200 W/m²
G_BZ = 0 W/m²
35 cells
K35
Current I in Amps
Voltage V in Volts
0
1
2
3
0
5
10
15
20

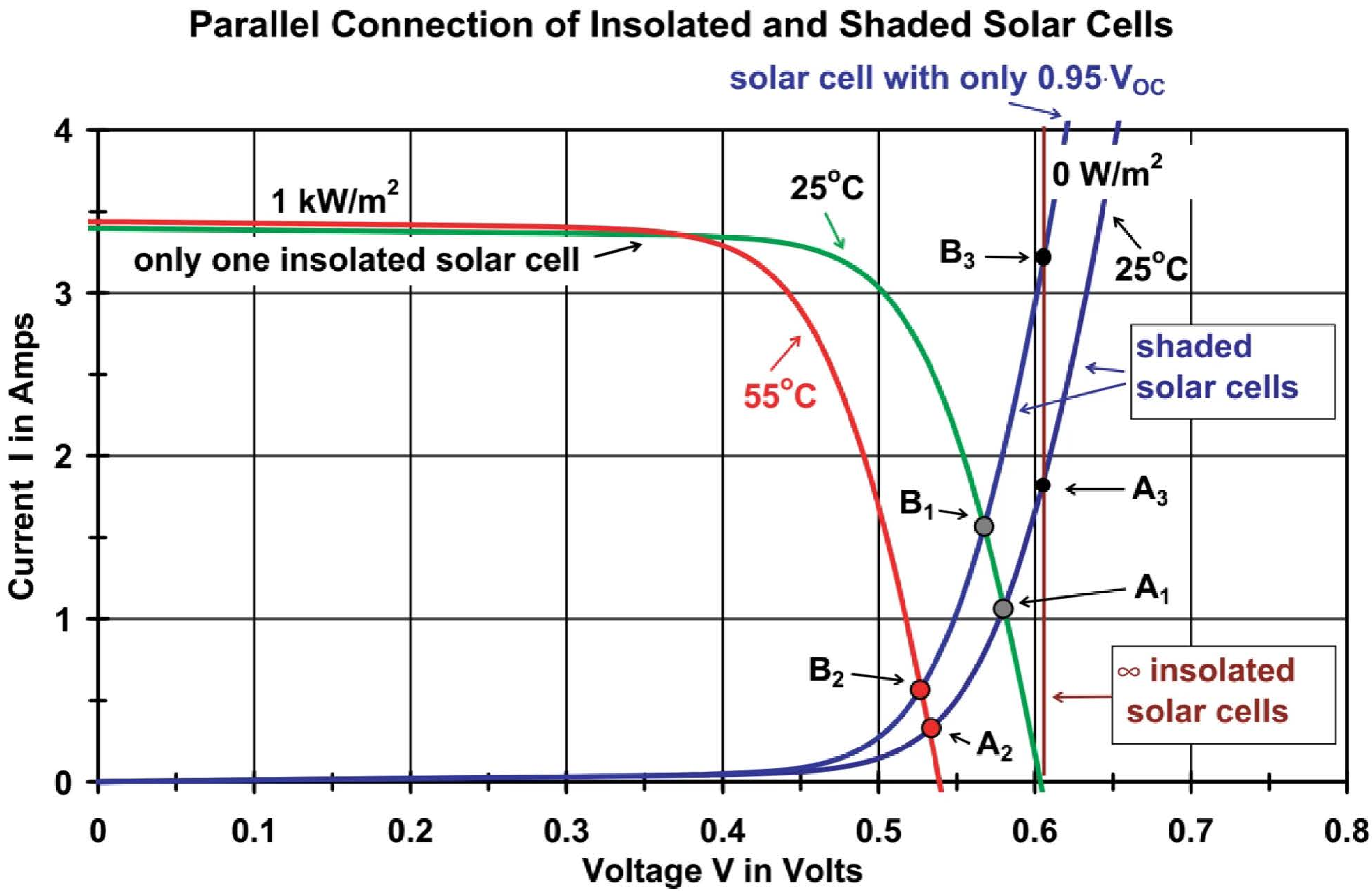


Measured values

ITEM	AVG TEMP	DiffMean
Whole Image	30.8	–7.9
R Ref	38.7	0.0
S01	50.4	11.7

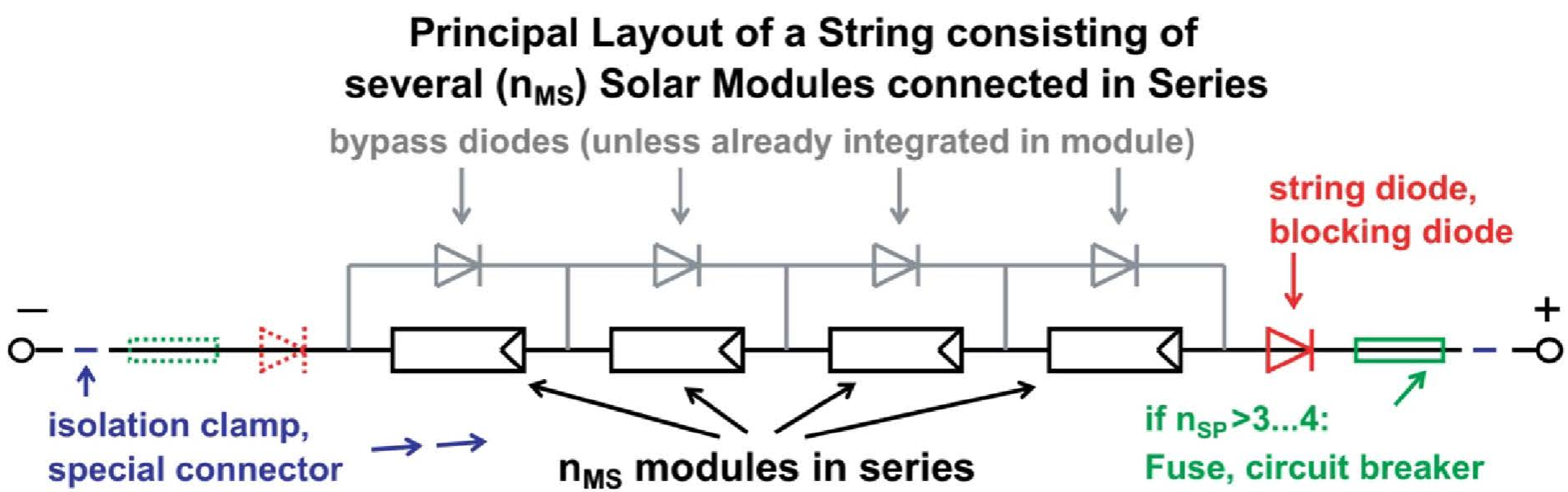
Connecting multiple cells



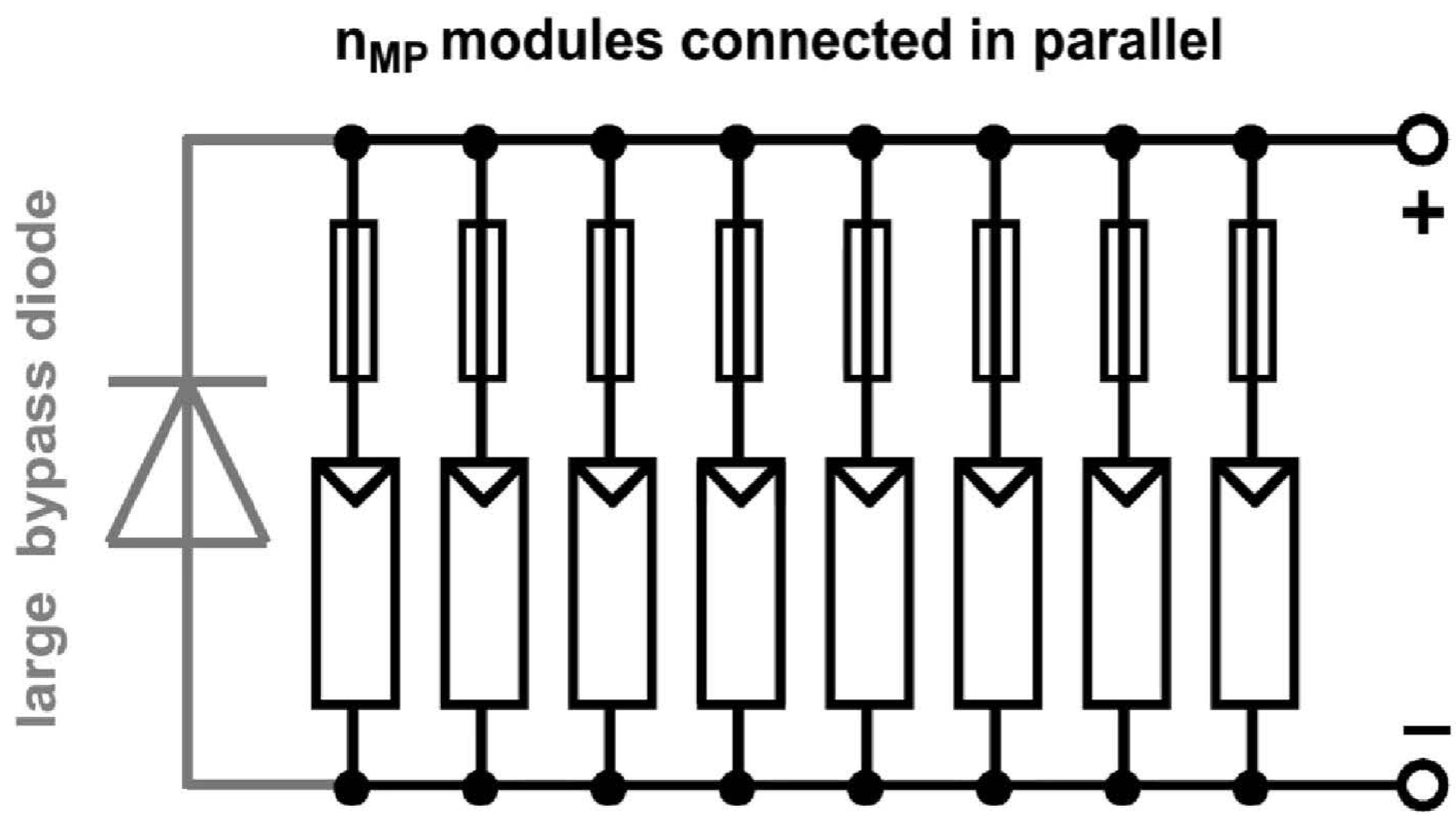


Parallel Connection of Insolated and Shaded Solar Cells
solar cell with only 0.95·V_OC
1 kW/m²
only one insolated solar cell
25°C
55°C
0 W/m²
25°C
B3
B1
B2
A3
A1
A2
shaded solar cells
∞ insolated solar cells
Current I in Amps
Voltage V in Volts
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

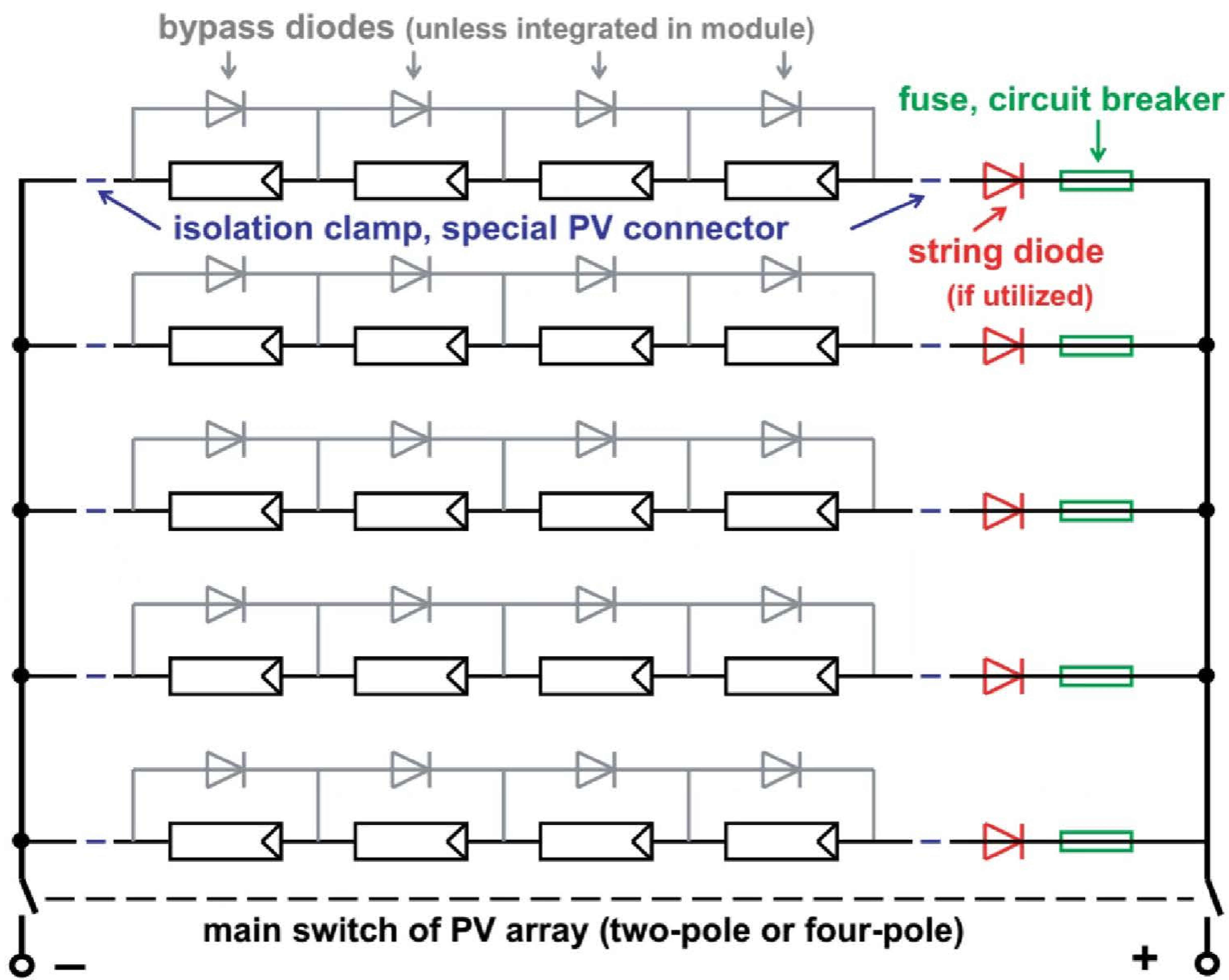
Connecting multiple cells



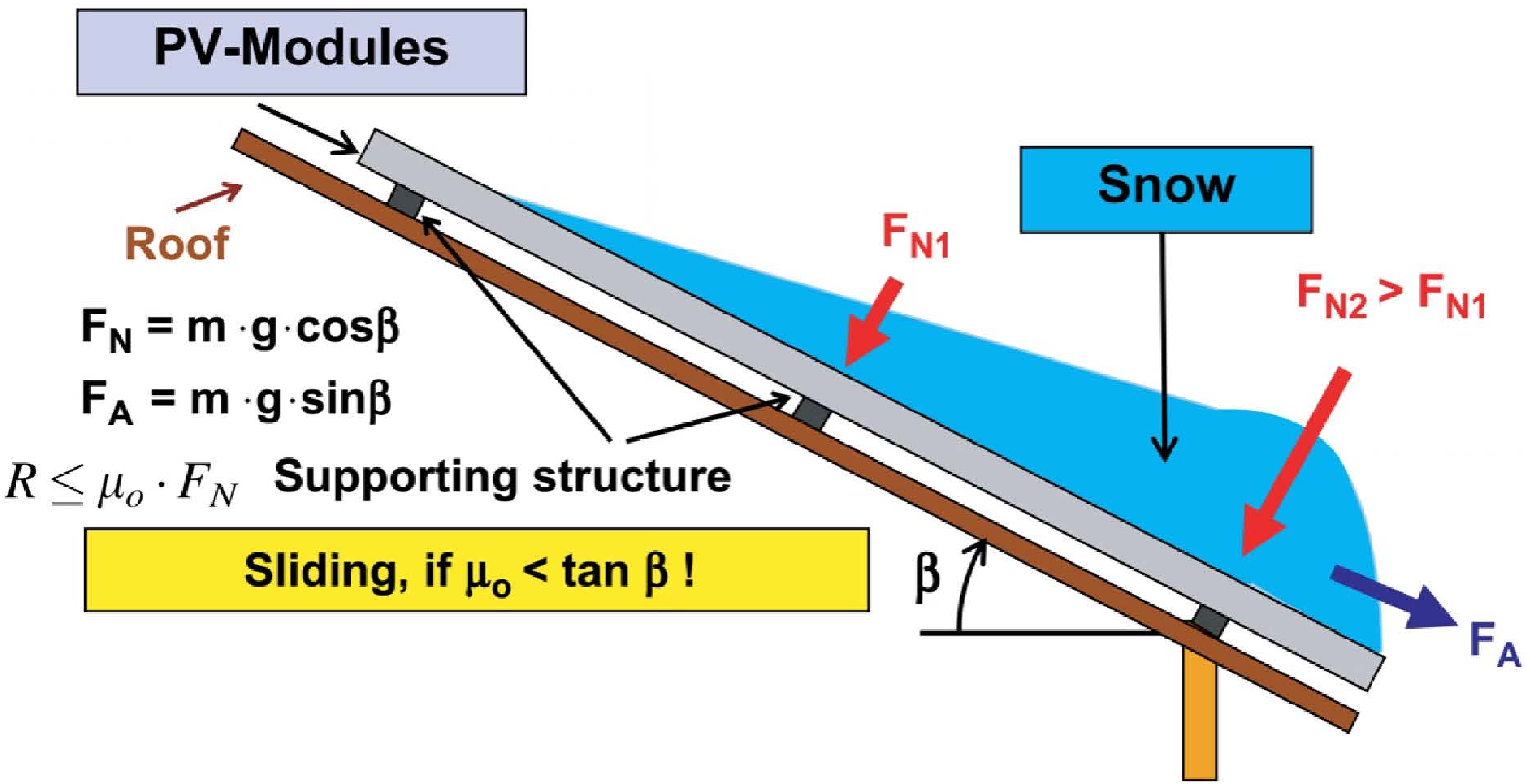
Connecting multiple modules

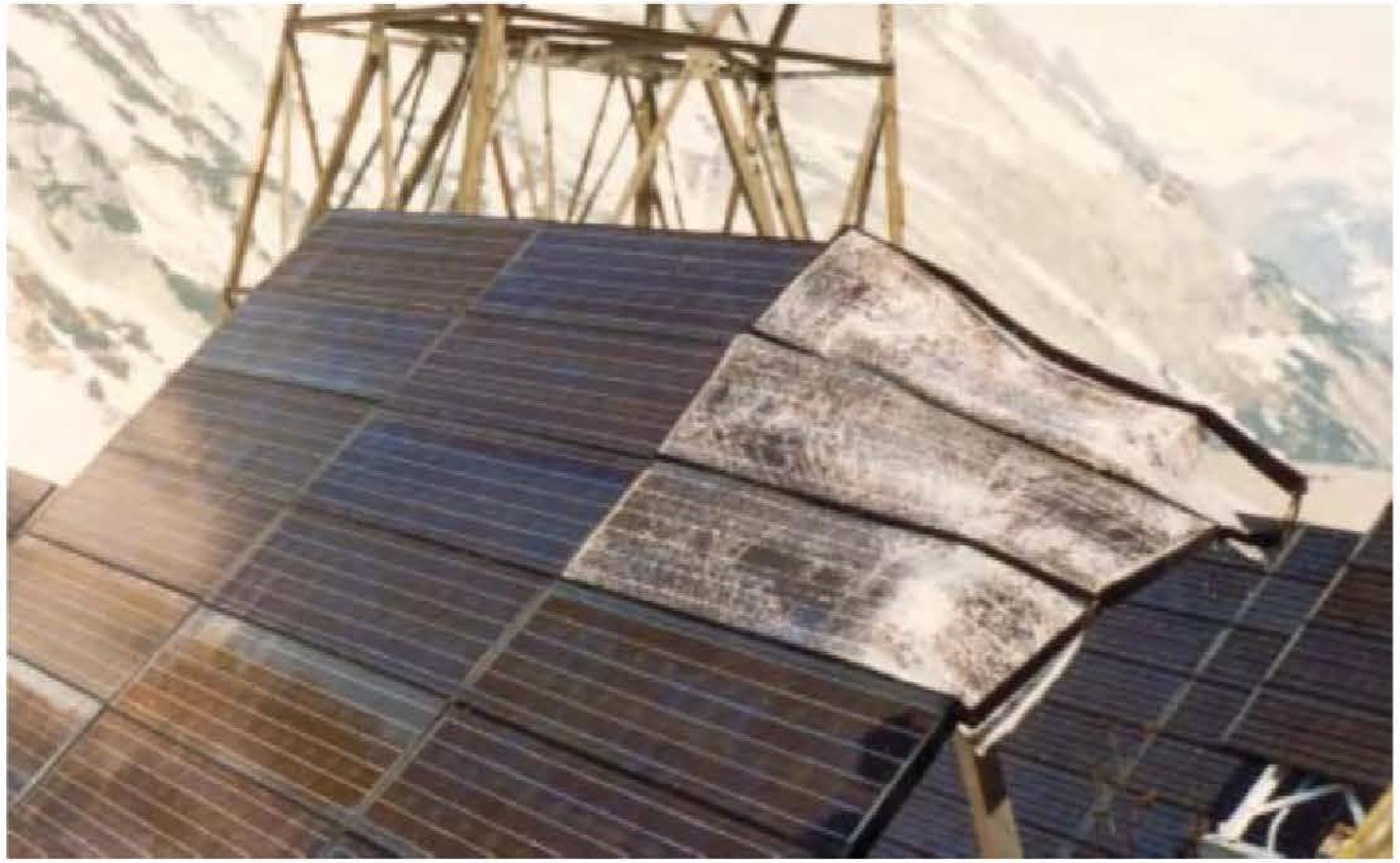


Connecting multiple modules



Weather factors: Snow





Weather factors: Wind

Dynamic pressure $q = \frac{1}{2} \cdot d_L \cdot v^2$

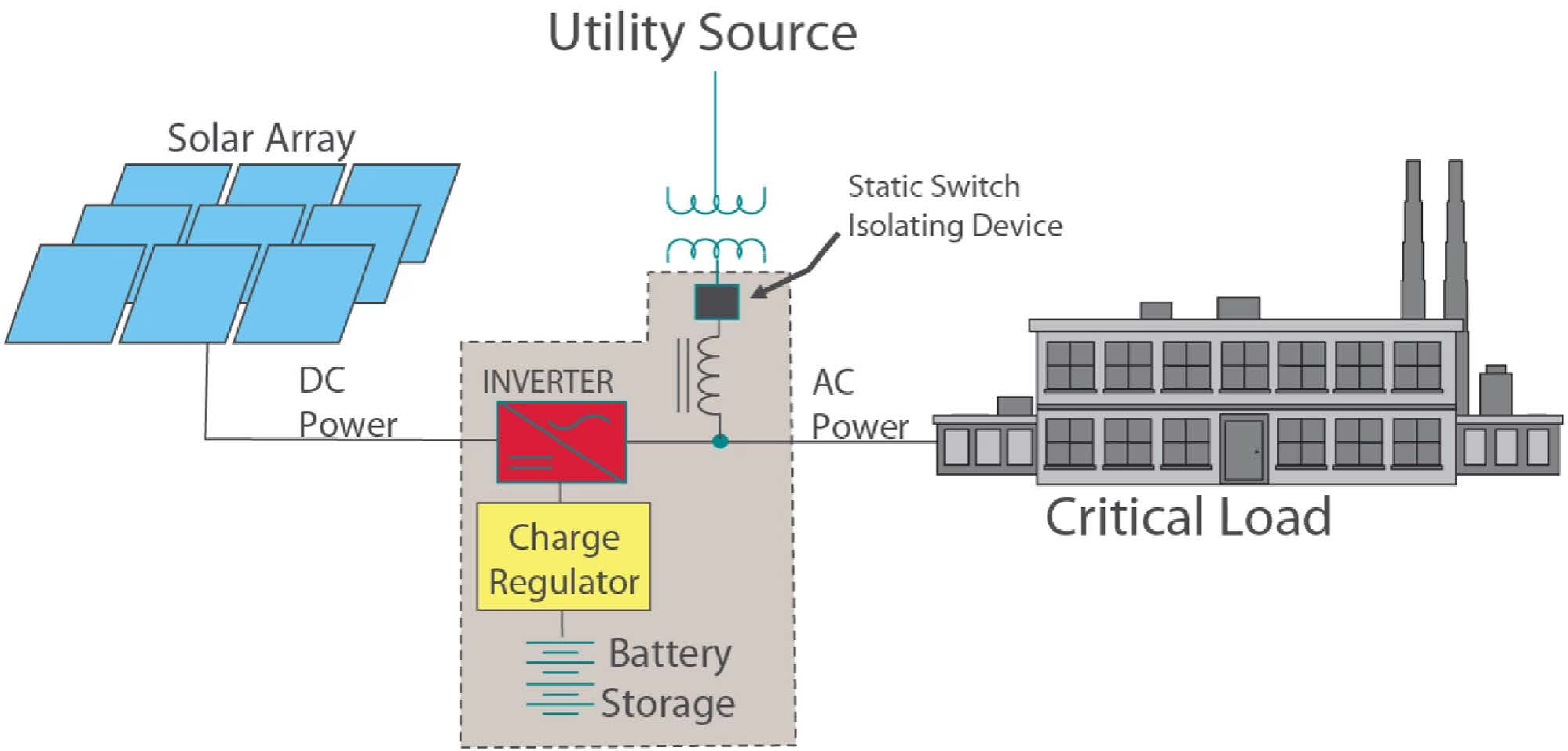
Wind force $F_W = c_W \cdot q \cdot A_G$

d_L is air density (which at 0 °C at sea level is 1.29 kg/m^3)

solar generator area A_G

direction of flow coefficient c_W 0.4 to 1.6

PV Assisted UPS



The ohmic resistance R of a wire with length l and gauge a is calculated as follows using specific resistance ρ of the wire material:

$$R = \rho \cdot \frac{l}{A}$$

For copper, ρ at 20 °C is around 0.0175 Ω mm²/m and at 85 °C is around 0.022 Ω mm²/m. To use the equation above correctly with these ρ values, l must be expressed in m and A in mm², and for two-wire cables must be twice as large as the wire length.

To determine the ohmic loss in solar generator wiring, only one equivalent loss resistance R_{DC} should be determined. For n_{SP} strings wired in parallel with one resistance R_{STR} each and a main DC cable with resistance R_H, the ohmic loss is determined as follows:

$$\text{Equivalent DC loss resistance: } R_{DC} = R_H + \frac{R_{STR}}{n_{SP}}$$

$$\text{Ohmic loss } P_{VR} \text{ on the DC side: } P_{VR} = R_{DC} \cdot I_{DC}^2$$

$$\text{DC loss } P_{VD} \text{ at string diodes: } P_{VD} = V_F \cdot I_{DC}$$

$$\text{Total loss } P_V \text{ on the DC side: } P_{VDC} = P_{VR} + P_{VD}$$

$$\frac{P_{VDCn}}{P_{DCn}} = \frac{R_{DC} \cdot I_{DCn} + V_F}{V_{DCn}}$$

Mono-crystalline Solar Cell

	Conversion Efficiency (%)	Average Conversion Efficiency (%)	Rated Power (Wp)	Max.Power Current, Imp (A)	Max.Power Voltage, Vmp (V)	Short Circuit Current, Isc (A)	Open Circuit Voltage, Voc (V)	Fill Factor (%)
	<10.00	<10.000	<1.49	<3.24	<0.460	<4.07	<0.585	<62.6
	10.00-11.00	10.500	1.56	3.35	0.465	4.19	0.587	63.4
	11.00-12.00	11.500	1.71	3.66	0.467	4.50	0.589	64.5
	12.00-13.00	12.500	1.86	3.97	0.469	4.74	0.591	66.4
	13.00-14.00	13.500	2.00	4.24	0.472	4.91	0.592	68.8
	14.00-14.25	14.125	2.10	4.33	0.485	4.92	0.604	70.6
	14.25-14.50	14.375	2.13	4.38	0.488	4.92	0.604	71.9
	14.50-14.75	14.625	2.17	4.44	0.489	4.93	0.604	73.0
	14.75-15.00	14.875	2.21	4.47	0.494	4.94	0.606	73.8
	15-00-15.25	15.125	2.25	4.51	0.498	4.94	0.607	74.9
	15.25-15.50	15.375	2.28	4.55	0.502	4.96	0.609	75.6
	15.50-15.75	15.625	2.32	4.58	0.506	4.98	0.612	76.1
	15.75-16.00	15.875	2.36	4.62	0.510	5.02	0.615	76.4
	16.00-16.25	16.125	2.39	4.67	0.512	5.06	0.617	76.6
	16.25-16.50	16.375	2.43	4.71	0.515	5.11	0.619	76.8
	16.50-16.75	16.625	2.47	4.76	0.518	5.15	0.621	77.1
	16.75-17.00	16.875	2.51	4.81	0.521	5.20	0.623	77.3
	17.00-17.25	17.125	2.54	4.85	0.523	5.25	0.624	77.5
	17.25.-17.50	17.375	2.58	4.90	0.526	5.29	0.626	77.8

*Under standard test condition: 1000W / m^2, AM 1.5, 25℃

*All figures bear±2% of tolerance

Polycrystalline silicon solar cell

Efficiency	Power	Max Power Current	Max Power Voltage	Short Circuit Current	Open Circuit Voltage	Fill Factor
Eff(%)	Ppm(W)	Ipm（A）	Vpm（V）	Isc（A）	Voc(V)	FF(%)
16.50-16.70	4.04	7.877	0.513	8.376	0.619	77.92
16.30-16.50	3.99	7.795	0.512	8.309	0.618	77.70
16.10-16.30	3.94	7.715	0.511	8.244	0.616	77.58
15.90-16.10	3.89	7.634	0.509	8.162	0.615	77.50
15.70-15.90	3.85	7.584	0.507	8.108	0.613	77.46
15.50-15.70	3.80	7.526	0.505	8.064	0.611	77.12
15.30-15.50	3.75	7.485	0.501	8.025	0.610	76.60
15.10-15.30	3.70	7.439	0.498	7.957	0.609	76.35
14.90-15.10	3.65	7.378	0.495	7.893	0.607	76.18
14.70-14.90	3.60	7.306	0.493	7.816	0.606	76.00
14.50-14.70	3.55	7.251	0.490	7.774	0.604	75.60
14.30-14.50	3.50	7.181	0.488	7.711	0.602	75.40
14.10-14.30	3.45	7.110	0.486	7.669	0.601	74.85

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